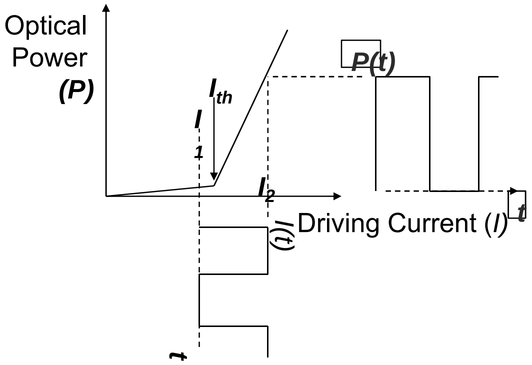
Radio over Fiber - An Optical Technique for Wireless Access

Xavier Fernando
Ryerson Communications Lab
Toronto, Canada
http://www.ee.ryerson.ca/~fernando

Motivation

Digital Fiber Optic Links

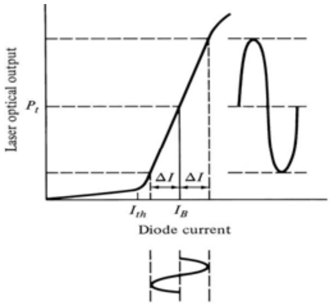
Digital information modulates the light signal in binary (on/off) or M-ary manner



Example:
Most current networks such as SONET, Ethernet, GPON, EPON are digital

Radio over Fiber (ROF) Links

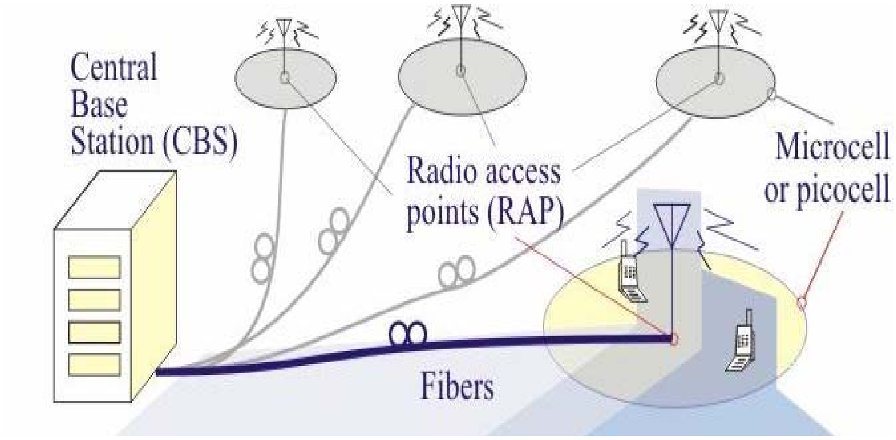
Radio frequency (analog) waveform (with embedded baseband information) continuously modulates the light wave



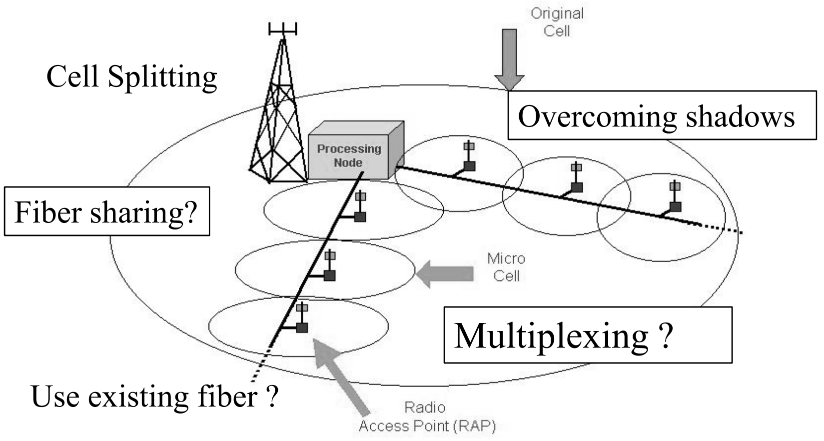
also referred to as
Microwave Photonic Links

Examples:
CATV
Satellite base station links
Fiber-Wireless systems

ROF based Fiber-Wireless (Fi-Wi) Access Network



A More Practical Architecture



Cell Splitting

Overcoming shadows

Fiber sharing?

Multiplexing ?

Use existing fiber ?

Fi-Wi Architecture

- Optical fibers transmit the RF signal between central-base station (CBS) and low power Radio Access Point (RAP).
- The RAP then transmits/receive the RF signal to customer units over the air.
- The RAPs only implement optical to RF conversion and RF to optical conversion.
- No DSP at RAP to keep it simple

  IF over fiber is also sometimes considered, but needs up/down conversion

Fi-Wi System

- ✓Makes the air-interface shorter
  - ✓This enables truly broadband access by reducing multi path delay spread (ISI) and often offering line of sight links
- ✓Enables Micro/Pico cellular architecture at low cost
  - ✓This increases frequency reuse and boost network capacity
  - ✓Reduce power consumption and size of the portable units (especially for 4G)

Fi-Wi System

- ✓Enables rapid deployment (Sydney Olympics example)
- ✓Provides coverage to special areas like
  - ✓Underground tunnels, mines, subway stations
  - ✓Highways and railway lines
- ✓Potential to use existing fiber
- ✓Ideal for mm-wave bands

$$Loss \propto 1/\lambda^2$$

Fi-Wi for 4G

- 4G promises 100 Mb/s to 1 Gb/s over air
- Peak RF power is proportional to bit rate times (carrier frequency$^{2.6}$) [Adachi].
- Example
  - If 8 kb/s needs 1W power at 2GHz, then 100 Mb/s at 5 GHz will need 135 kW power.
- Impossible with regular hand held devices
- Therefore the cell size should be significantly reduced (e.g. from 1000 m → 34 m radius)

Why Fiber?

- Lowest attenuation → 0.2 dB/km at 1.55 μm band. This is much smaller than attenuation in any other cable
  - The attenuation is independent of the modulation frequency
  - Much greater distances are possible without repeaters
- Highest Bandwidth (broadband)
  - Single Mode Fiber (SMF) offers the lowest dispersion → highest bandwidth → up to several tens of GHz
- Low Cost for fiber itself
- Possibility of using existing dark/dim fiber

History

- Fi-Wi concept started in early 1990s. Ortel™. Motorola ™ were early players.
- Considered for Boston (USA), New Castle (UK) subway coverage
- There was no real need for ROF (and broadband) at that time
- Now there is a renewed interest
  - There is plenty of dark/dim fiber around
  - Technology has matured
  - Low cost photonic devices and high cost spectrum

Sydney Olympics 2000 Example

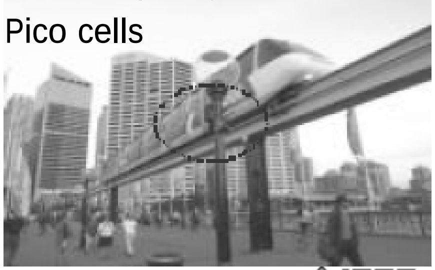
- Telstra's Millennium Network used ~1.5 million km fiber
- Delivered audio, video, and data from the Olympic Games to the world.
- 24 hours a day for sixty days,
- The Millennium Network reached four billion people at any time, with an estimated total of 25 billion people.

(http://literature.agilent.com/litweb/pdf/5988-4221EN.pdf)

Sydney Olympics Cont…

Britecell™

- > 500 Remote Antennae
- Over 500,000 wireless calls
- Multi operator system (3 GSM operators)
- Multi standard radio (900/1800 MHz)
- Dynamic allocation of network capacity
- In building and external Pico cells

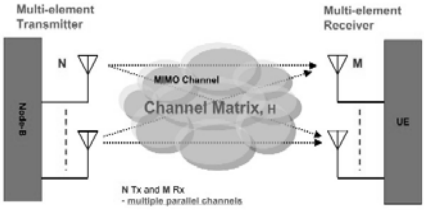


ROF for MIMO

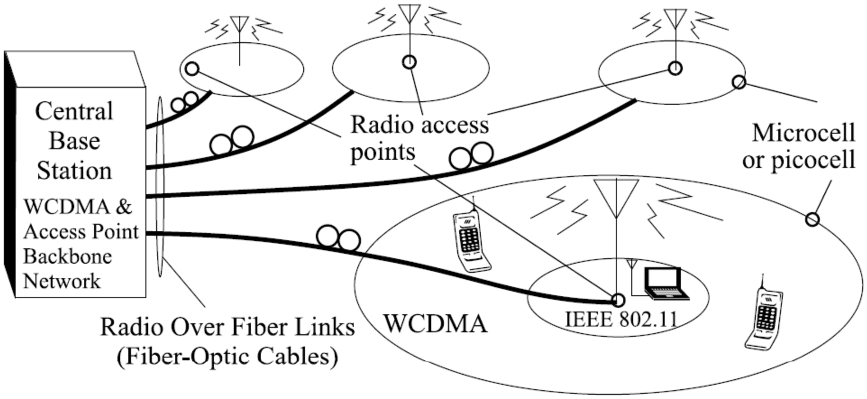
Beyond 3G initiative in China code named FUTURE

Multiple antennas in a single ROF cell will allow multiple-input multiple-output (MIMO) transmission technology to be applied

(http://www.china-cic.org.cn/english/digital%20library/200412/10.pdf)



Multi System Possibility

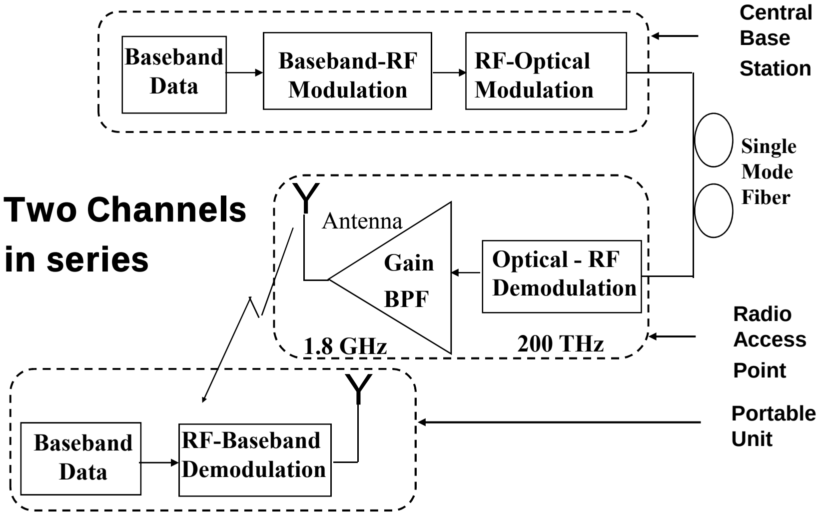


Both WCDMA and WLAN interfaces supported by one antenna

- Within Pico cell → Wi-Fi access
- Within Micro cell → high-speed WCDMA access
- Out of Micro cell → regular WCDMA access

The ROF Link Basics

Closer Look of Fi-Wi Link



Baseband Data → Baseband-RF Modulation → RF-Optical Modulation ← Central Base Station

Single Mode Fiber

Two Channels in series

Antenna

Gain BPF ← Optical - RF Demodulation

1.8 GHz

200 THz

Radio Access Point

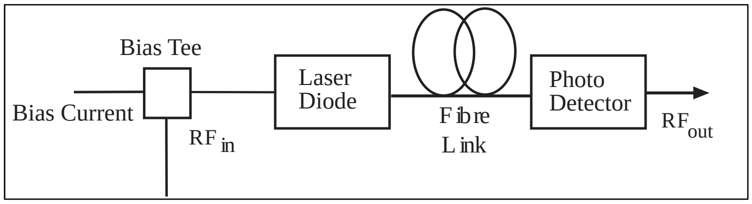
Baseband Data ← RF-Baseband Demodulation

Portable Unit

Two Types of Modulation

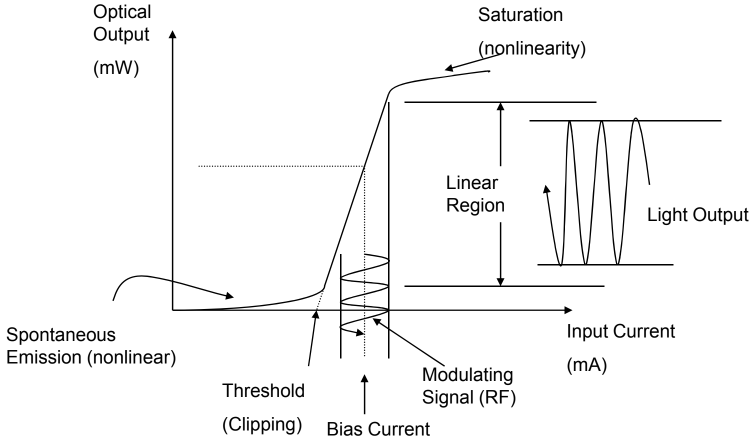
- Baseband-RF Modulation
  - Typical digital wireless modulation schemes such as QPSK, GMSK or QAM
  - Decided by the wireless system operator
  - ROF engineer usually don't have control
- RF-Optical modulation
  - ROF engineer have control
  - Can be direct or external modulation
  - Can be intensity or coherent modulation

Direct Intensity Modulation



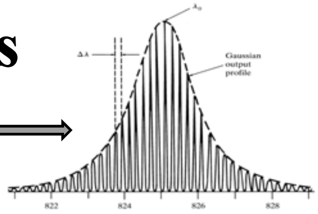
- The message signal (RF) is superimposed on the bias current (dc) which modulates the laser
- Robust and simple, hence widely used
- Issues: laser resonance frequency, chirp, clipping and laser nonlinearity

Direct Intensity Modulation of Laser Diode

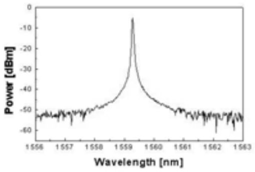


Types of Lasers

- Fabry-Perot Laser
  - Multiple longitudinal modes
  - Medium noise and distortion

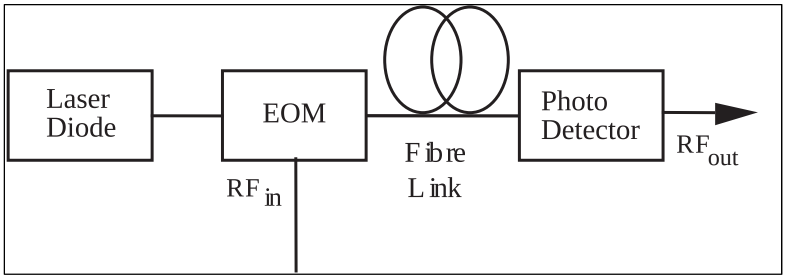


- Distributed Feed Back Laser
  - Single longitudinal mode
  - Low noise and distortion



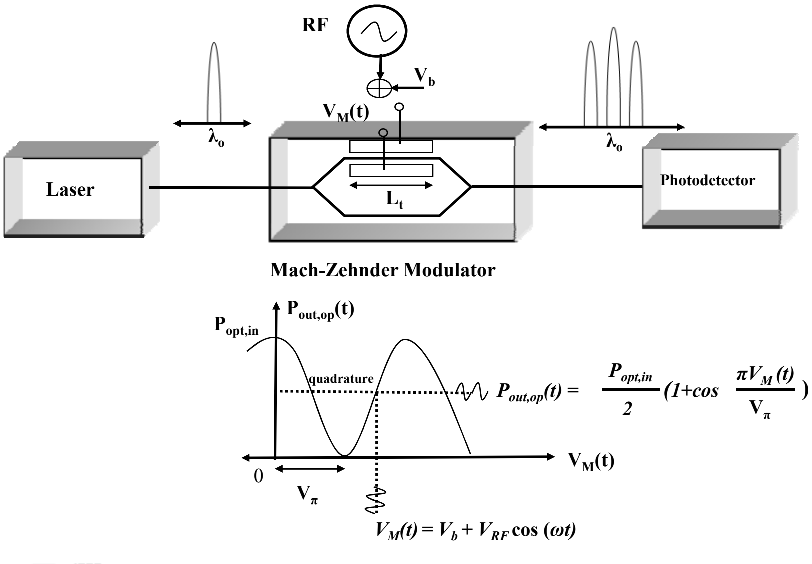
- Vertical Cavity Surface Emitting Lasers
  - Simple coupling to fiber
  - Mainly short wavelength
  - Higher noise and distortion

External Intensity Modulation



- Modulation and light generation are separated
- Offers much wider bandwidth → up to 60 GHz
- More expensive and complex
- Used in high end systems (no chirp)
- Still nonlinearity is a concern

Mach Zehnder Modulator



$$P_{out,op}(t) = \frac{P_{opt,in}}{2}\left(1+\cos\frac{\pi V_M(t)}{V_\pi}\right)$$

$$V_M(t) = V_b + V_{RF}\cos(\omega t)$$

Mach Zehnder Modulator

- Incoming light is split into two paths
- Electric field applied to one path which introduces a phase shift *mπ*
- When *m* is
  - odd → constructive interference
  - even → destructive interference at the output
- Traveling wave type electrodes improve bandwidth

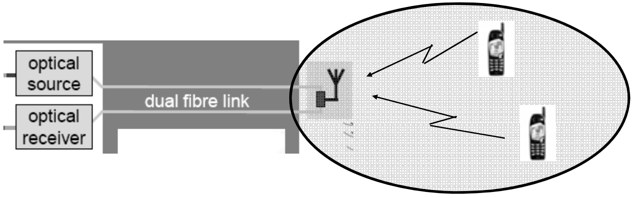
Electro Absorption Modulator

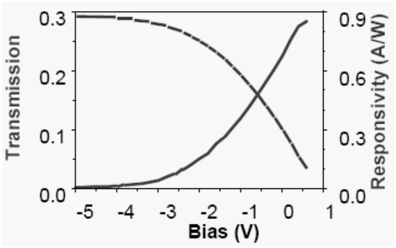
An EAM modulates the light by a change in the absorption spectrum caused by an applied electric field

EAM can operate with much lower voltages at very high speed (tens of gigahertz)

EAM can work as a photo detector for the downlink and modulator for uplink

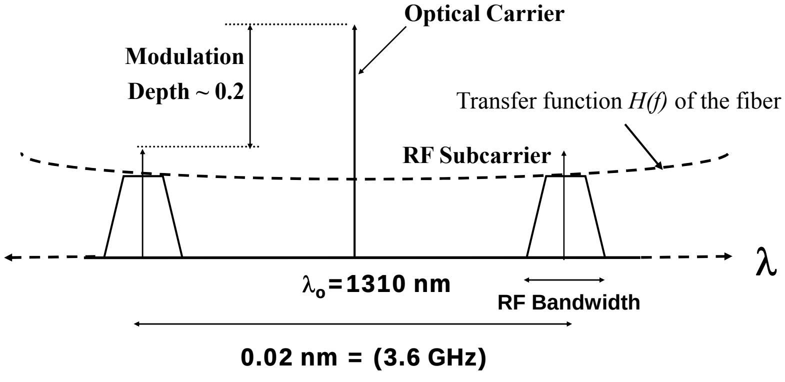
Electro Absorption Modulator





- An ideal single device RAP
- Demonstrated by British Telecom
- Very low power pico cells

RF Spectrum in the Fiber

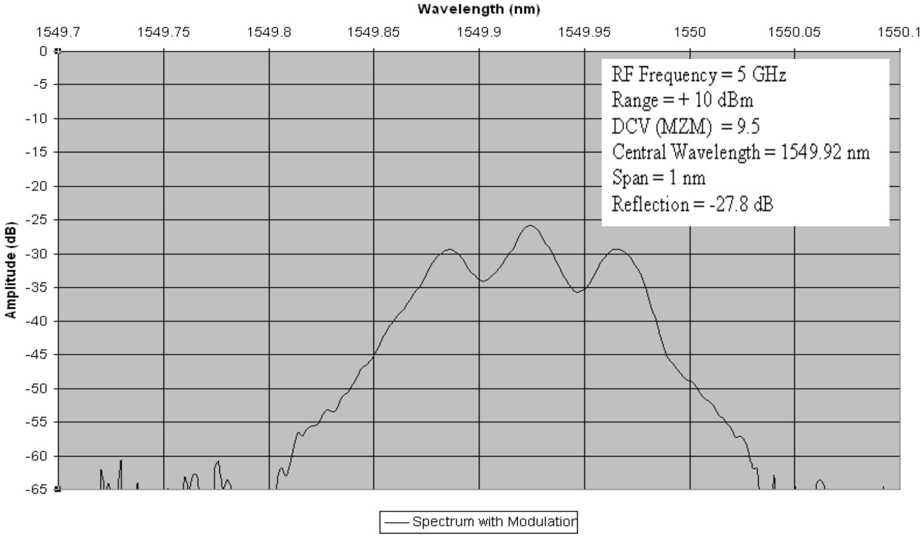


$H(f) = exp[-j\alpha(\lambda)l(f-f_o)^2]$;

l: length, α:Dispersion factor

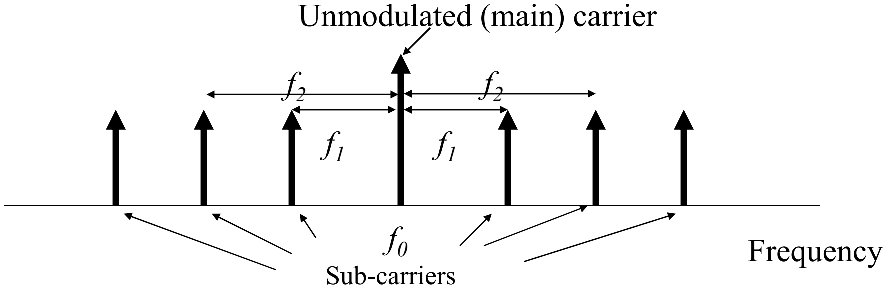
Fiber dispersion will rotate the phase of sidebands

Spectrum with 5 GHz RF Sidebands

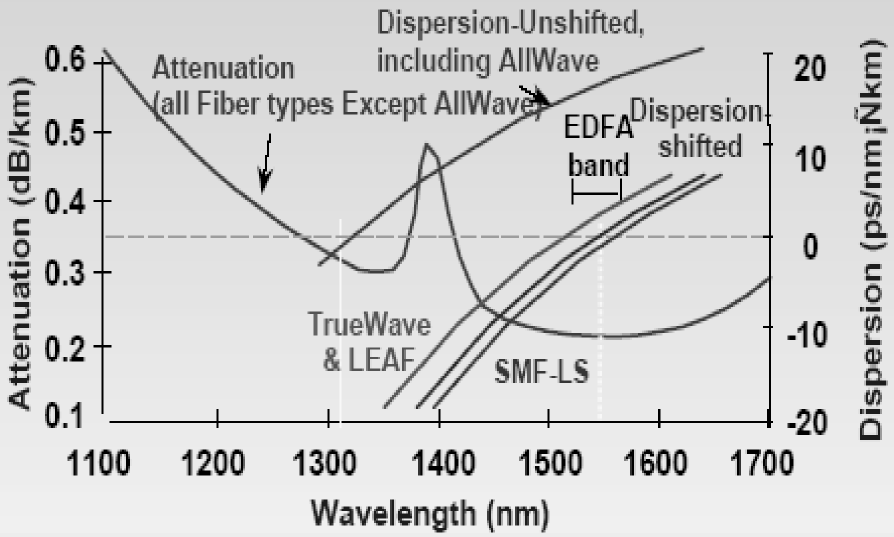


RF Frequency = 5 GHz
Range = + 10 dBm
DCV (MZM) = 9.5
Central Wavelength = 1549.92 nm
Span = 1 nm
Reflection = -27.8 dB

Sub Carrier Multiplexing



- SCM → Frequency division multiplexed (FDM) multiple RF carriers
- Each modulating RF is a sub-carrier
- Unmodulated optical signal is the main carrier

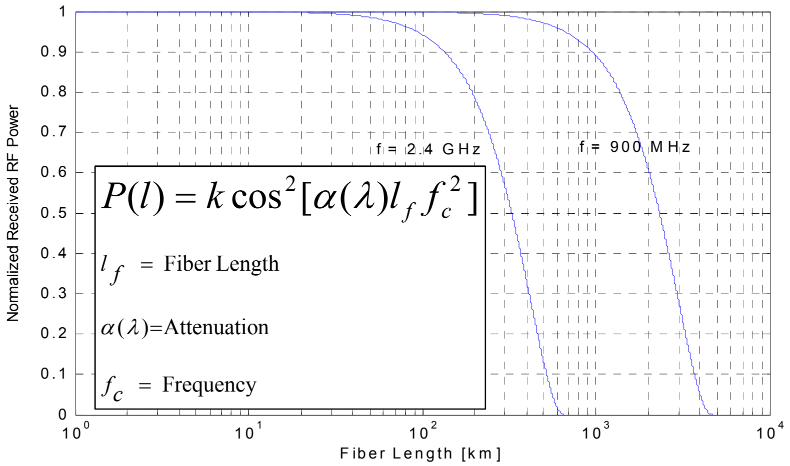


The Fiber

Fiber Dispersion

- Typical intensity modulation creates double sideband transmit carrier spectrum
- Fiber group velocity dispersion (GVD) causes phase shift between the USB and LSB
- At specific fiber distance l_f the phase shift can be 180° → sideband cancellation
- Several single side band schemes are developed, especially at mm-wave bands

Fiber Dispersion & Sideband Cancellation at λ = 1550 nm

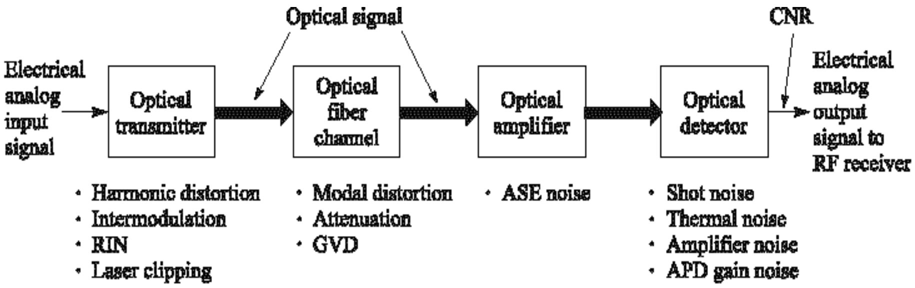


Photodiodes

This convert the received light wave signal to electrical current (O/E)

- Positive-Intrinsic-Negative (*pin*) photodiode
  - No internal gain
  - Robust and widely used
- Avalanche Photo Diode (*APD*)
  - An internal gain of *M* due to self multiplication
  - Requires high reverse bias voltage (~40V)
  - Expensive and used only in high end systems

Noise/Distortions in ROF Links



Optical signal

CNR

Electrical analog input signal

Optical transmitter

Optical fiber channel

Optical amplifier

Optical detector

Electrical analog output signal to RF receiver

- Harmonic distortion
- Intermodulation
- RIN
- Laser clipping

- Modal distortion
- Attenuation
- GVD

- ASE noise

- Shot noise
- Thermal noise
- Amplifier noise
- APD gain noise

- Modal distortion– only in multimode fiber
- Attenuation – depends on wavelength
- GVD – Group velocity distortion

Noise in Photo Detector

$$\left\langle i_Q^2 \right\rangle = 2qI_p BM^2 F(M)$$

Quantum (Shot) Noise

F(M): APD noise figure
q = electron charge
M = Avalanche Gain
I_p: Mean detected current
B = Bandwidth

Quantum noise is proportional to *mean* optical power
Large unmodulated carrier results in high shot noise

$$\left\langle i_T^2 \right\rangle = 4K_B TB / R_L$$

Thermal noise
Depends on the load resistance
R_L and constant

Relative Intensity Noise

- RIN exist only in analog (ROF) links
- Typically RIN is assumed to be proportional to the *square* of the mean optical power $\langle I_{RIN}^2 \rangle = P_{RIN} \Re^2 P_o^2 B$
- We have shown that RIN also increases with the RF power $<s_i^2(t)>$ and modulation depth *m* → *Signal dependent noise*

$$\langle I_{RIN}^2 \rangle = P_{RIN} \Re^2 P_o^2 B [1 + \sum_{i=1}^{n} m_i^2 \langle s_i^2(t) \rangle]$$

(Optical) Signal to Noise Ratio

- OSNR is the signal power divided by the sum of all noise powers
- They may not have equal weight

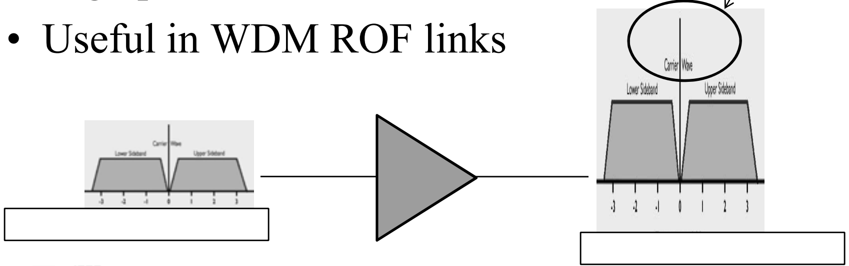
$$SNR = \frac{\langle i_p^2 \rangle M^2}{\left[2q(I_p + I_D) M^2 F(M) + 4k_B T / R_L + (RIN) I_p^2 \right] B}$$

- RIN nonlinearly increases in SCM links

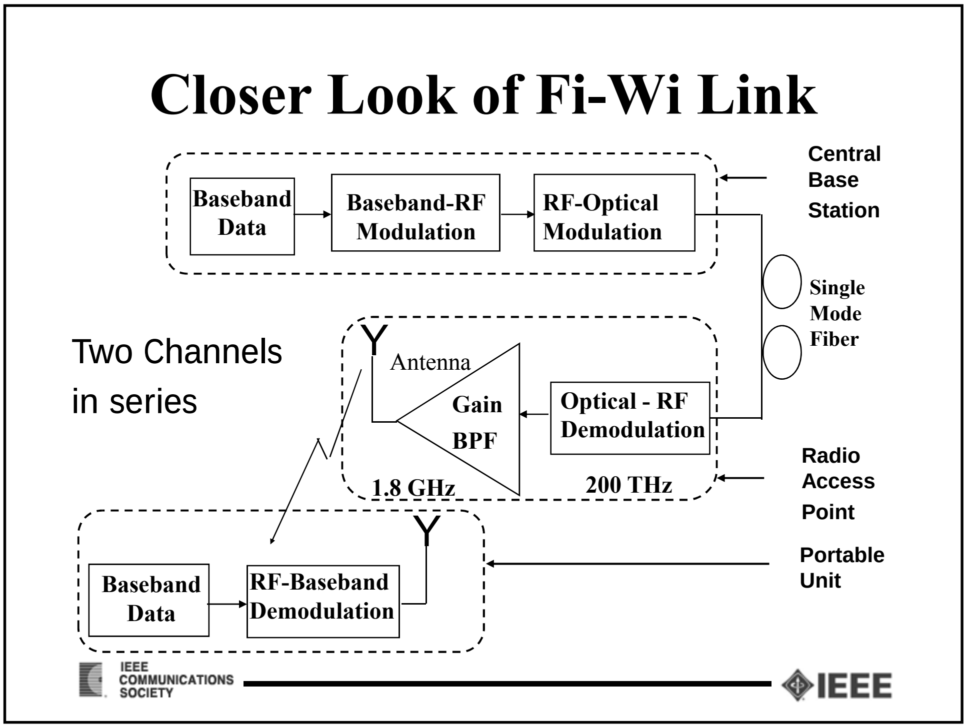
SNR can NOT be improved by amplification

Optical Amplifier?

- Optical amplifier amplifies sidebands plus carrier
- Also add noise (ASE)
- Not very useful in single wavelength ROF links
- High power carrier will flood the detector
- Useful in WDM ROF links



Power Budget of Fi-Wi Links



Closer Look of Fi-Wi Link

Baseband Data
Baseband-RF Modulation
RF-Optical Modulation

Central Base Station

Single Mode Fiber

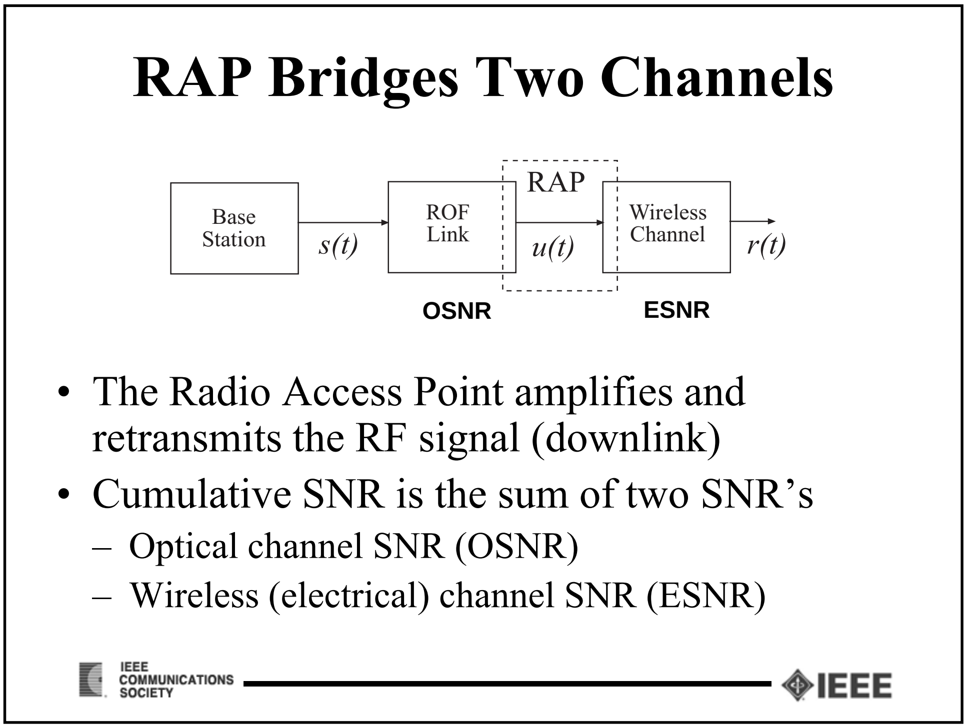
Two Channels in series

Antenna
Gain
BPF
Optical - RF Demodulation
1.8 GHz
200 THz

Radio Access Point

Baseband Data
RF-Baseband Demodulation

Portable Unit



RAP Bridges Two Channels

Base Station
s(t)
ROF Link
RAP
u(t)
Wireless Channel
r(t)
OSNR
ESNR

- The Radio Access Point amplifies and retransmits the RF signal (downlink)
- Cumulative SNR is the sum of two SNR’s
  - Optical channel SNR (OSNR)
  - Wireless (electrical) channel SNR (ESNR)

Impedance Matching Loss

Impedance Matching is an issue at both the transmitter and receiver

- Forward biased Laser has very low impedance
- Reverse biased photodiode has very high impedance
- Resistive impedance matching gives wide bandwidth, but high loss (~ 40 dB – ORTEL)
- Reactive impedance matching techniques (with L,C) reduce loss and also bandwidth (~10-20 dB)

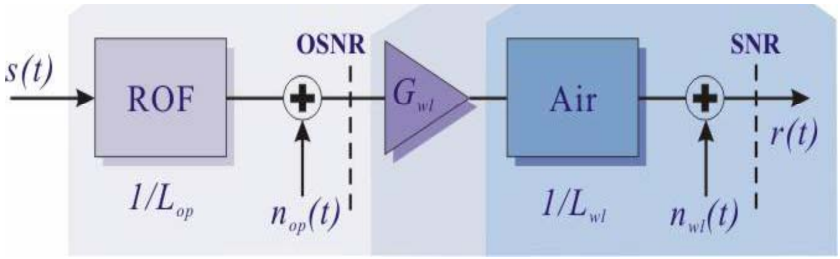
Loss in the Optical Link

- Loss due to E/O and O/E Conversion
  - 39 dB with resistive matching [*Ortel]
  - 20 dB with reactive matching
- Fiber loss (α dB/km) increases with length (l) and appears twice in the electrical domain

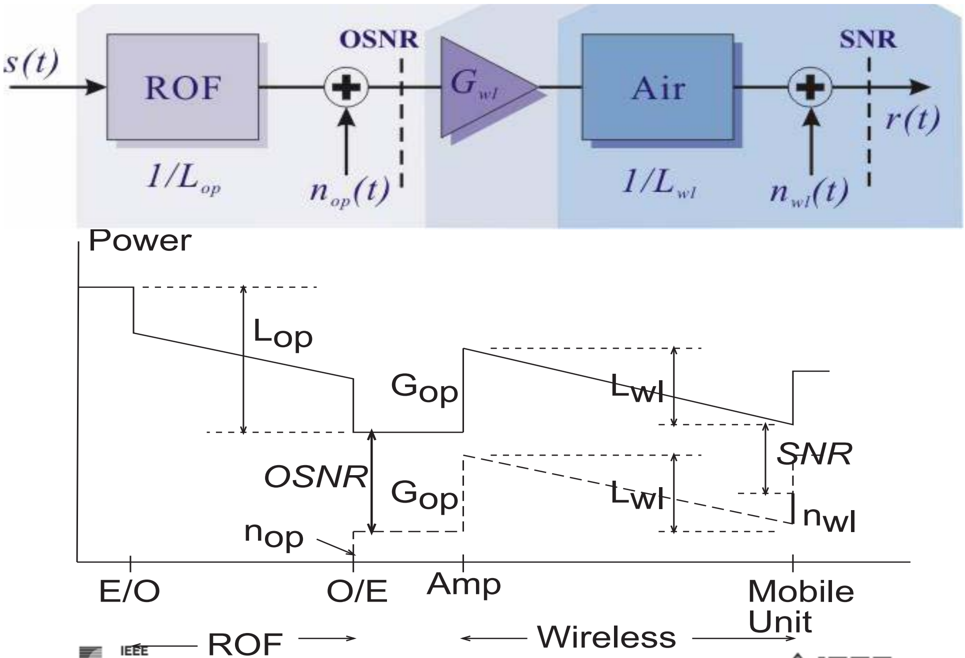
$$L_{op} = 20\text{dB} + 2\alpha(\lambda) l_f$$

- Optical noise is added at the RAP where, the signal is lowest

Cumulative SNR



- The noise is added twice (at the optical and wireless receivers) where the signal is weak.
- The overall SNR is the weighted sum of the two SNRs and smaller than the smallest SNR.



Cumulative SNR

- L_{op} – depends on wavelength - $\alpha(\lambda)$ dB/km
- n_{op} – optical link noise = $\langle I_{sh}^2 \rangle + \langle I_{RIN}^2 \rangle + \langle I_{th}^2 \rangle$
- $G_{op} = G_{wl}$ – Amplifier Gain
- L_{wl} – Path loss in the air interface
- OSNR – SNR at the RAP
- SNR – SNR at the portable

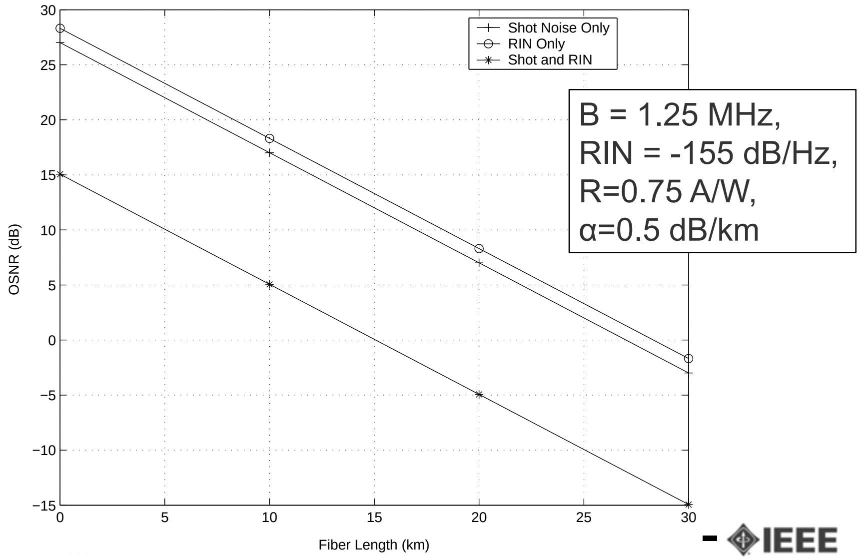
$$\mathrm{OSNR} = \frac{m^2 I_D^2 E[s^2(t)] 10^{-L_{op}/10}}{\langle I_{shot}^2 \rangle + \langle I_{RIN}^2 \rangle + \langle I_{th}^2 \rangle}$$

$$\boxed{SNR = \frac{OSNR}{\left(1 + 10^{L/10} \big/ G_{op}\right)}}$$

Concatenated Channel

- Week signal plus noise is amplified and transmitted at the RAP
- More noise added in the air and at the portable receiver
- Both signal and noise go through wireless channel loss
- Optical and Radio noises dictate the SNR
- Acceptable SNR at the cell boundary dictates the cell size

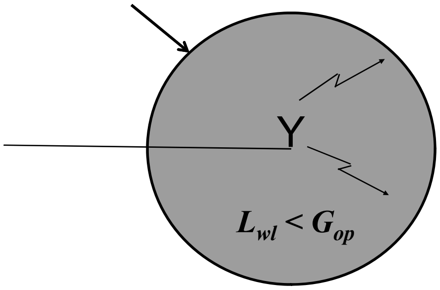
OSNR Vs Fiber Length



B = 1.25 MHz,
RIN = -155 dB/Hz,
R=0.75 A/W,
α=0.5 dB/km

Some Observations

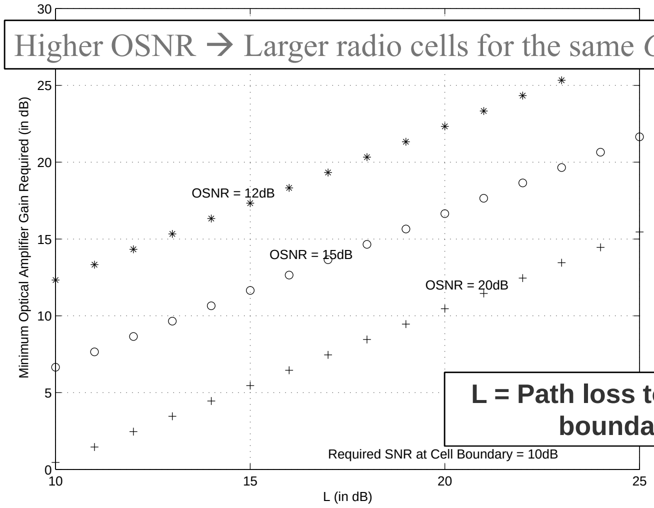
- **There is an inverse relationship between the radio cell size and the fiber length**
- **Closer to the RAP (when $L_{wl} < G_{op}$), the optical link noise dominates**



$$n(t) = \frac{n_{op}(t)G_{op}}{L_{wl}} + n_{wl}(t)$$

Wireless channel noise and MUI dominates when $L_{wl} > G_{op}$

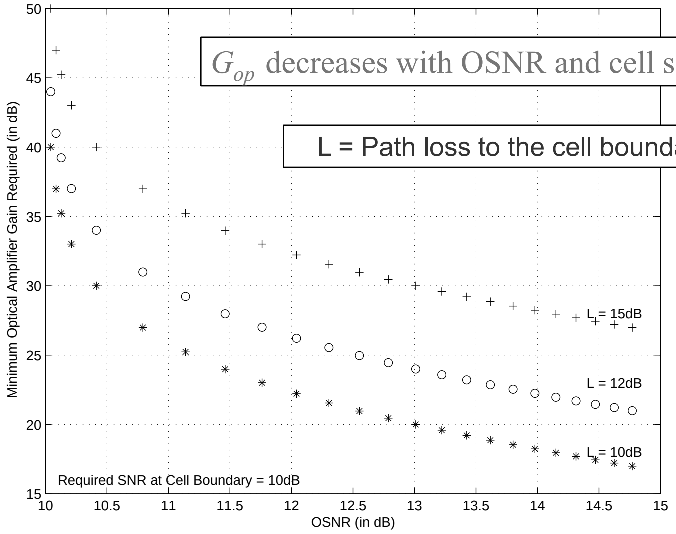
Optical Receiver Amp. Gain Vs Wireless Path Loss



Higher OSNR → Larger radio cells for the same G_{op}

L = Path loss to the cell boundary

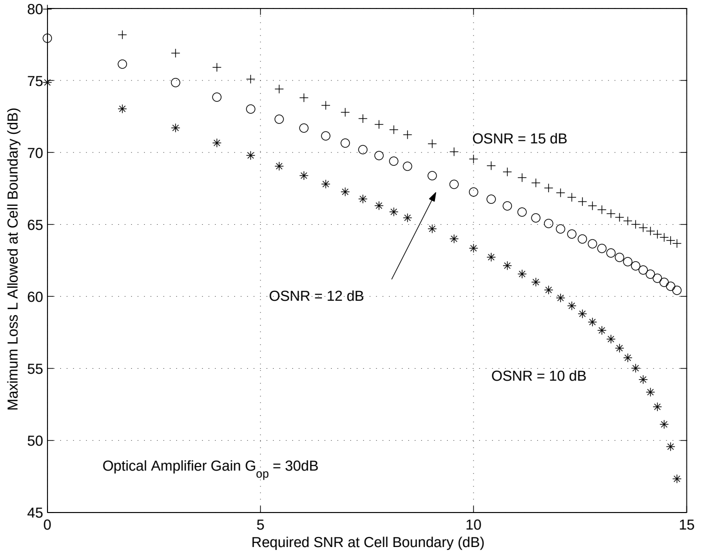
Minimum Amplification at RAP



G_{op} decreases with OSNR and cell size

L = Path loss to the cell boundary

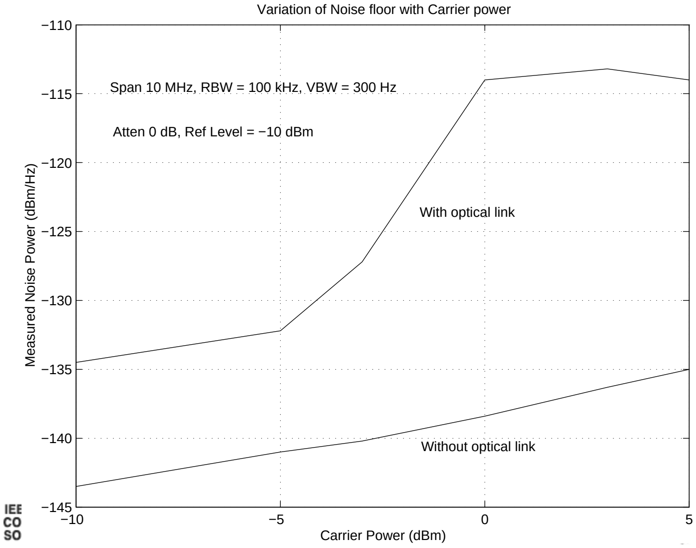
Radio Cell Size Vs SNR



Some Observations

- Loss and noise in the ROF link plays significant role in overall system performance
- Wider bandwidth RF signal collects more noise in the ROF link (CDMA)
- Lower modulation depth results in higher unnecessary quantum noise
- RIN nonlinearly increases in SCM systems
- E/O and O/E conversion loss reduction is key area of research

Nonlinear Increment in Noise



Nonlinear Distortion in ROF

Nonlinear Distortion

- Nonlinear distortion in the ROF links arises due to:
  - E/O Conversion at either laser diode or at Mach-Zehnder modulator
  - Nonlinearity of the receiver RF amplifier
- The former is of more crucial
- The nonlinearity combined with multipath propagation in the air interface creates problems

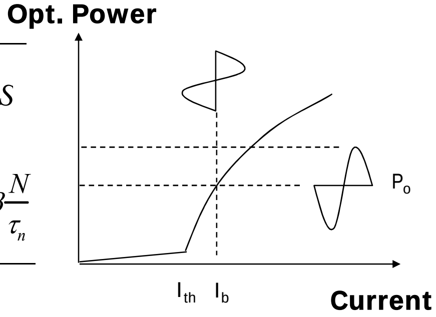
---

Laser Diode Nonlinearity

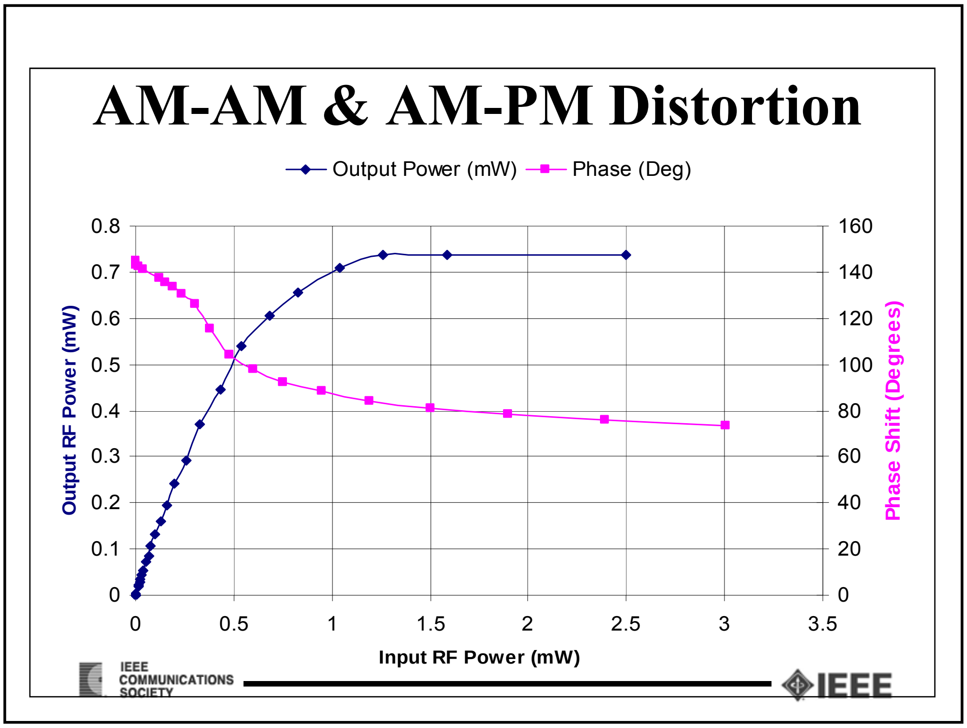
- **Rate equations**

$$\frac{dN}{dt} = \frac{I_A}{qV_{act}} - \frac{N}{\tau_n} - g_o(N - N_{og})(1 - \varepsilon S)S$$

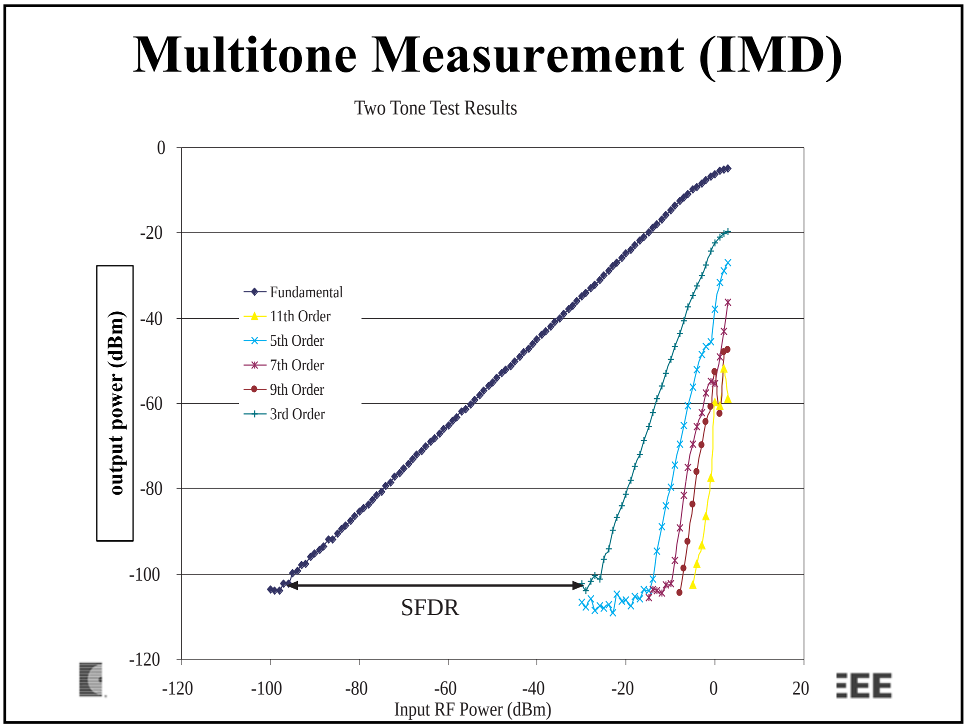
$$\frac{dS}{dt} = \left\{\Gamma g_o(N - N_{og})(1 - \varepsilon S) - \frac{1}{\tau_p}\right\}S + \Gamma\beta\frac{N}{\tau_n}$$



Large number of device dependant parameters make direct modeling very difficult [Vankwilkelberge et. al. 89]



AM-AM & AM-PM Distortion

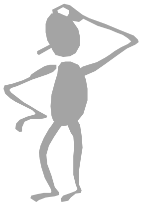


Multitone Measurement (IMD)

Nonlinearity Issues

Large linear dynamic range is required especially in the reverse link

Multipath fading & shadowing (40-60 dB)
Varying user distance (d) from RAP
Varying path loss ($d^{-1.5} \sim d^{-4.0}$)
Varying number of users
RF envelope fluctuation
(peak to average ratio)



Some Approaches to Solve NLD

- Opto/Electronic linearization approaches targeting the laser (mostly for analog CATV links).
  - Solving rate equations.
  - Laser circuit models.
  - Device Dependency

Laser is not the only concern in ROF

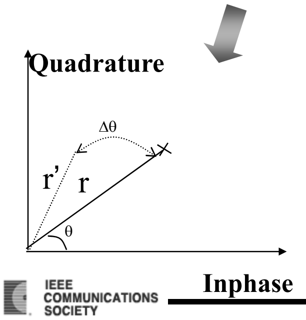
- Other techniques.
  - Modified channel assignment.
  - Automatic gain controllers (not for AM-PM)
  - Baseband DSP Solutions*

Baseband DSP Approach

- A baseband model for (nonlinear) fiber and (multipath) wireless channel
- A suitable channel estimation protocol
- An asymmetric compensation scheme
  - Predistortion + equalization (downlink)
  - A novel joint compensation (uplink)
- Fairly independent of ROF link specifics

Bandpass Nonlinear Systems

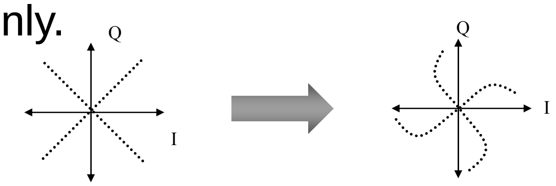
- Carrier re-growth issues like harmonics and IMD are big concern in multicarrier systems
- In band distortion: AM-AM and AM-PM is always a concern



A bandpass memoryless nonlinear system can be a modeled with a baseband nonlinear model.
(Saleh et. al. 1981)

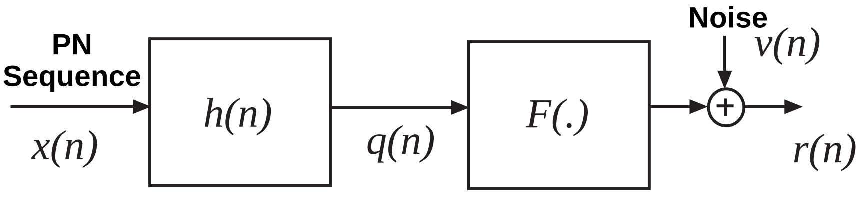
Signal Processing Preliminaries

- All the impairments would primarily result in amplitude and phase distortion of the vector modulated symbols plus noise only.



- With adequate sampling rate baseband DSP can be deployed for nonlinear distortion compensation.

Fiber-Wireless Uplink Estimation



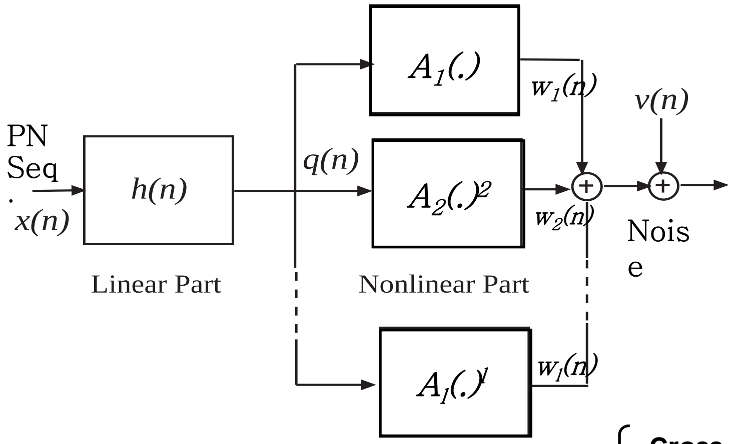
Linear Part
(Wireless Channel)

Nonlinear Part
(Optical Channel)

The cross correlation:

$$R_{rx}(s)\ \alpha\ \{h(s) + \text{higher order terms}\}$$

Fiber-wireless Uplink Estimation...

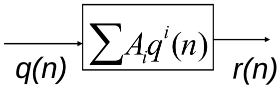


$R_{rx}(s) = R_{w_1x}(s) + R_{w_2x}(s) + \ldots + R_{w_lx}(s)$

Cross correlation terms

Fiber Wireless Uplink Estimation…

1. **Estimate the linear impulse response *h(n)***
   - By projecting each cross-correlation term into a different subspace
2. **Estimate the polynomial coefficients A_i**
   - *Q(n)* is estimated from using *h(n)*
   - *R(n)* is known
   - A_i are determined by QR decomposition method



Fiber Wireless Uplink Estimation...

1. Estimate the linear impulse response *h(n)* by generating *m* simultaneous equations.

- Transmit $\alpha_i x(n)$ instead of *x(n)* and repeat *m* times. *(1≤ i≤ m)* [Billings 80].

$$R_{r_{\alpha_i}x}(s) = \sum_{j=1}^{l} \alpha_i^{j} R_{w_j x}(s)$$

Estimating the polynomial weights A_i

- *q(n)* is estimated from *x(n)* and *h(n)*, *r(n)* is known

$$r(n) = \sum_{i=1}^{l} A_i q^{i}(n) + v(n)$$

$$\begin{bmatrix} q^{l}(1) & q^{l-1}(1) & \dots & q(1) \\ q^{l}(2) & q^{l-1}(2) & \dots & q(2) \\ \dots & \dots & \dots & \dots \\ q^{l}(N_c) & q^{l-1}(N_c) & \dots & q(N_c) \end{bmatrix} \begin{bmatrix} A_l \\ A_{l-1} \\ \dots \\ A_1 \end{bmatrix} = \begin{bmatrix} r(1) \\ r(2) \\ \dots \\ r(N_c) \end{bmatrix}$$

$$V_q \underline{A} = \underline{r}$$

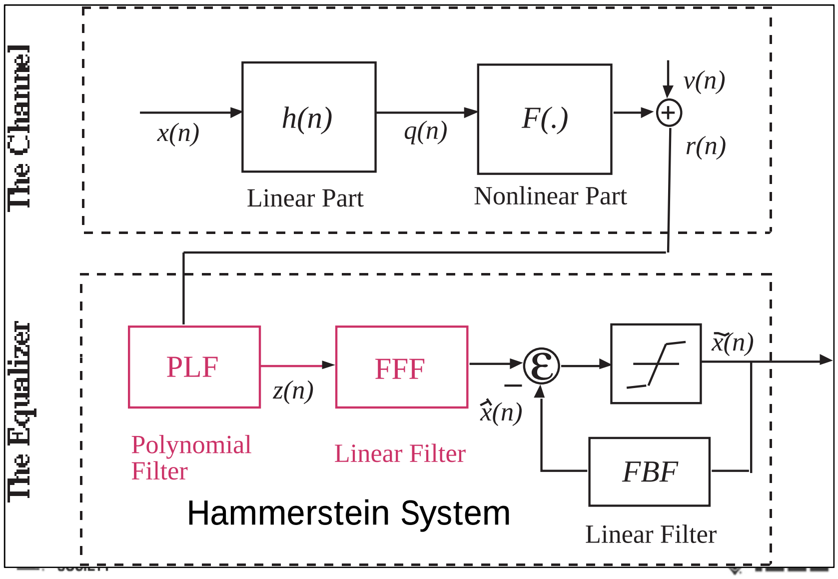
By decomposing,

$$V_q = QR$$

Finally

$$R\underline{A} = Q^{T}\underline{r}$$

A Unified Compensation



The Channel

x(n)

h(n)

Linear Part

q(n)

F(.)

Nonlinear Part

v(n)

r(n)

The Equalizer

PLF

Polynomial Filter

z(n)

FFF

Linear Filter

ε

$\hat{x}(n)$

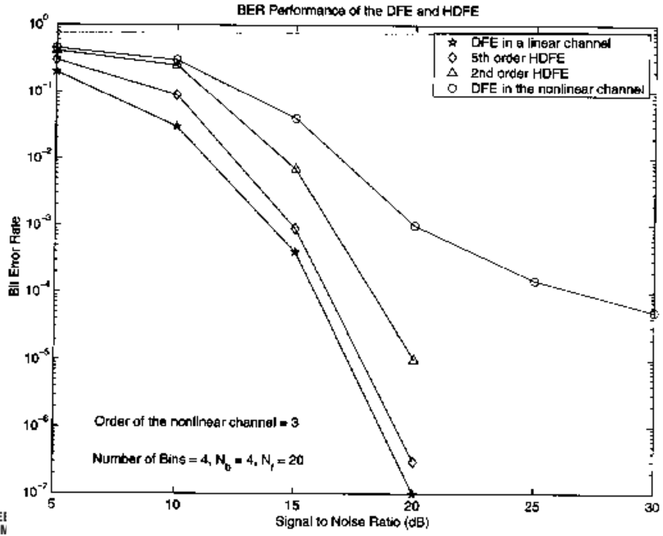
$\tilde{x}(n)$

FBF

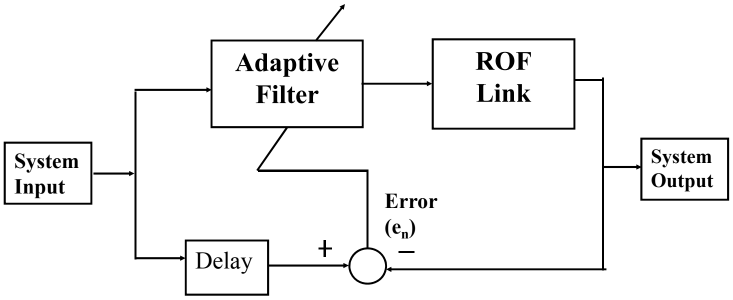
Linear Filter

Hammerstein System

BER Performance of the HDFE



Downlink Compensation


System Input

Adaptive Filter

ROF Link

System Output

Error (e_n)

Delay

+

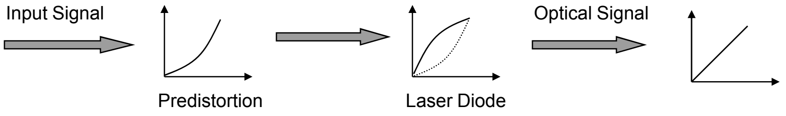
–

Adaptive predistortion to compensate nonlinear distortion

- Using a look-up table or
- Using a higher order adaptive filter

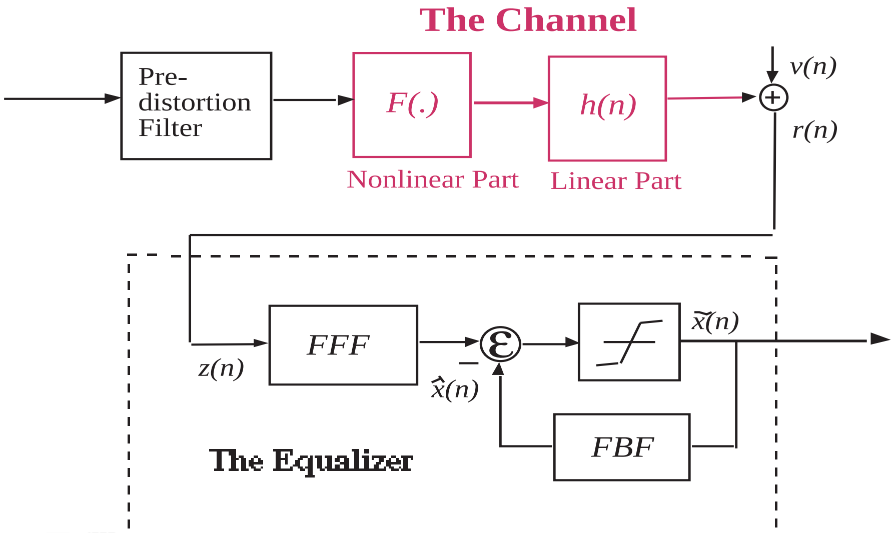
Predistortion

- The linearization can be done predistortion.
- The principle of predistortion is to create direct proportionality between the input signal and the optical output

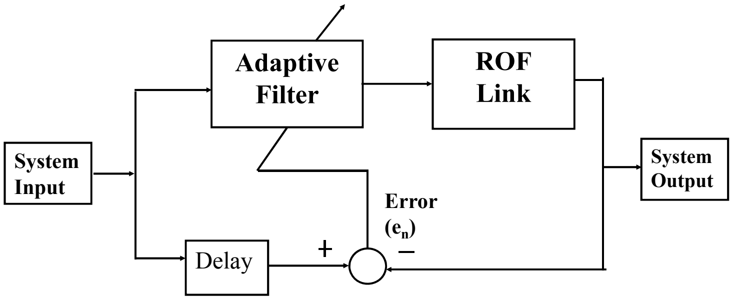


- Amplitude predistortion can NOT completely solve saturation
- It can improve the dynamic range to some extend

Downlink Compensation



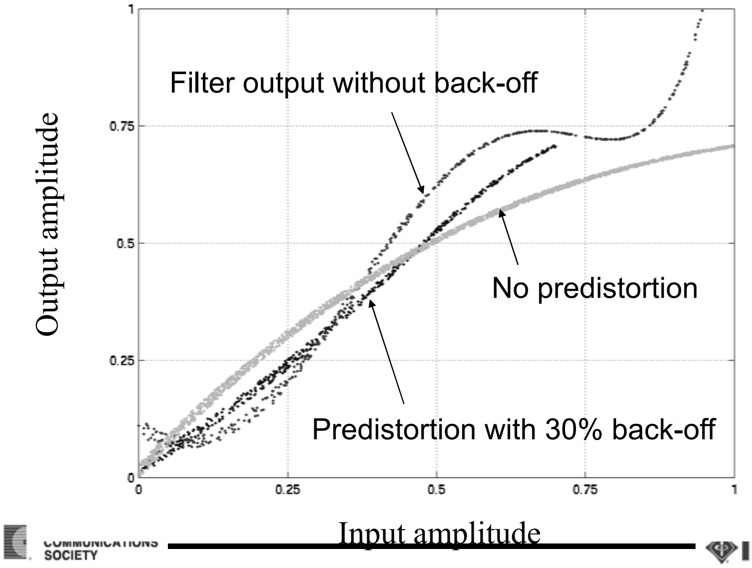
Downlink Compensation



Adaptive pre-distortion to compensate nonlinear distortion

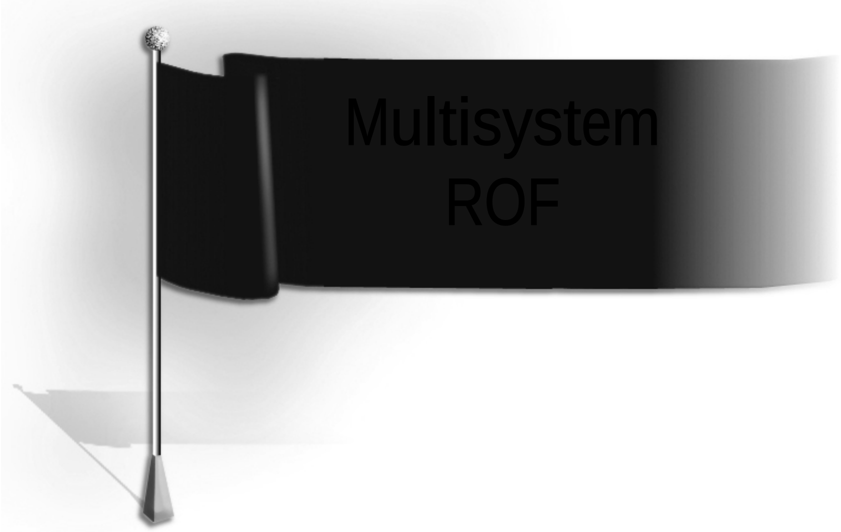
- Using a look-up table or
- Using a higher order adaptive filter

Amplitude Predistortion



Advantages of the DSP Solution

- Separate compensation for the dynamic wireless channel and the static fiber channel is possible
- Multiple users can share the same nonlinearity compensation
- Proposed solution has Modular architecture
- No modification is preferred in the portable unit
- Asymmetric distribution of complexity is desirable
- Device independent (adaptive) approach is possible

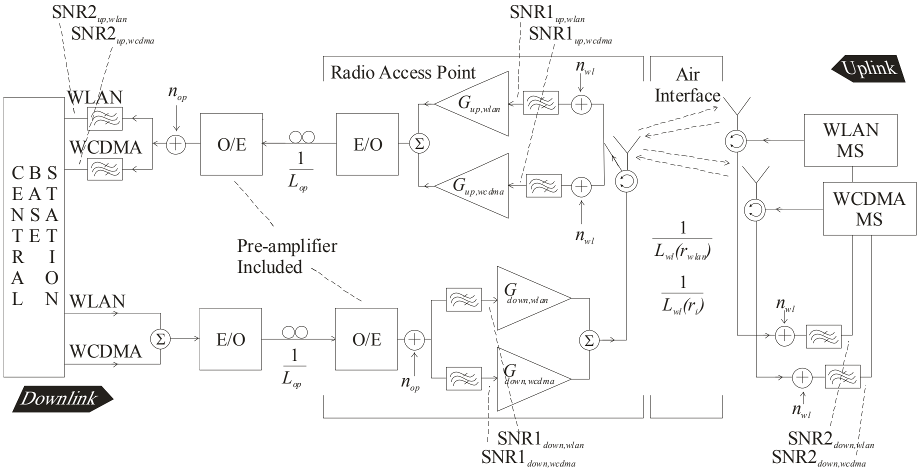


Multisystem ROF

Multisystem ROF

- When multiple RF signals are transmitted over fiber for Fi-Wi support, multitude of issues:
  - Noise, loss and power budget for each system
  - Nonlinearity and dynamic range issue for individual systems
  - Cross coupling among RF signals due to nonlinearity
  - Added RIN due to multiple carriers
  - Other (MAC layer) issues

WLAN and WCDMA



Design Issues

- Up/down link amplifier gain for each system
- Modulation depth for each system
- Cumulating noise and SNR for both systems (that depend on bandwidth, loss etc.)
- RF power and radio cell size for each system
- Nonlinear coupling among these systems
- Other wireless system issues (CDMA, OFDM etc)

Some Expressions

Cumulative Optical Modulation Index

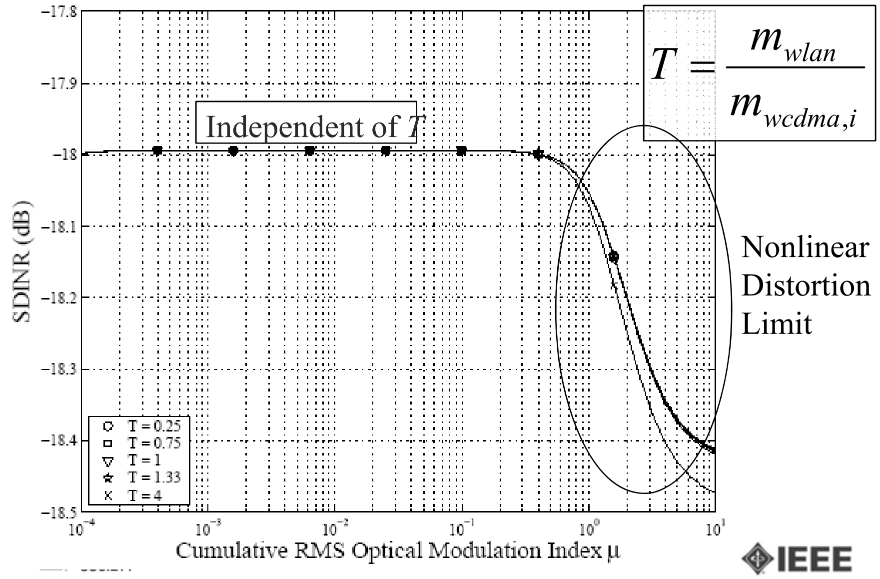
$$\mu = \sqrt{G_{\mathrm{up,wcdma}} \sum_{i=1}^{n} \frac{A_i^2}{2} + G_{\mathrm{up,wlan}} \left(\frac{B_\beta^2}{2} \right)} = \sqrt{\sum_{i=1}^{n} \frac{m_{\mathrm{wcdma},i}^2}{2} + \frac{m_{\mathrm{wlan}}^2}{2}}$$

$$\mathrm{SDINR}_{up,wcdma} = \frac{\langle D_{\mathrm{wcdma}}^2 \rangle}{\frac{G_{\mathrm{up,wcdma}}}{L_{\mathrm{op}}} \langle n_{\mathrm{up,wcdma}}^2 \rangle + \langle n_{\mathrm{op,wcdma}}^2 \rangle + \langle n_{\mathrm{cl,wcdma}}^2 \rangle + \sum_{i=1}^{7} \langle Z_i^2 \rangle}$$

$$\mathrm{SDNR}_{up,wlan} = \frac{\langle D_{\mathrm{wlan}}^2 \rangle}{\frac{G_{\mathrm{up,wlan}}}{L_{\mathrm{op}}} \langle n_{\mathrm{up,wlan}}^2 \rangle + \langle n_{\mathrm{op,wlan}}^2 \rangle + \langle n_{\mathrm{cl,wlan}}^2 \rangle + \sum_{i=1}^{3} \langle M_i^2 \rangle}$$

IEEE

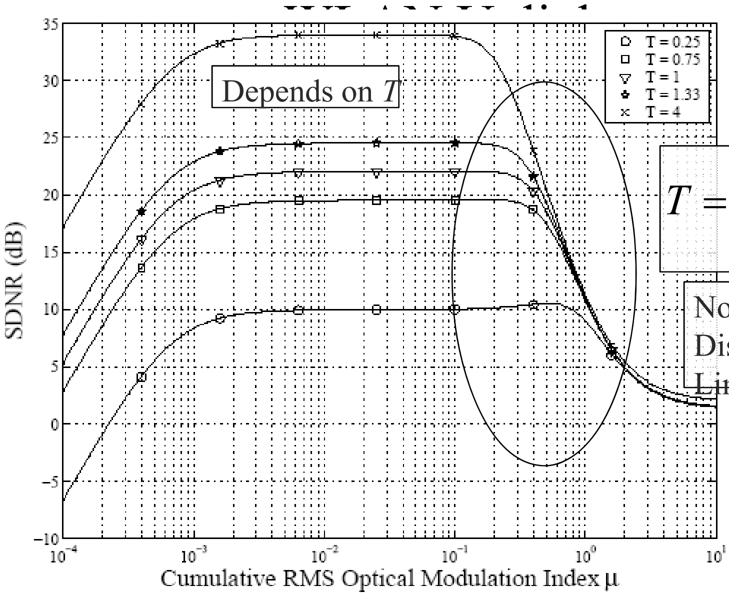
WCDMA Uplink



$$T = \frac{m_{wlan}}{m_{wcdma,i}}$$

Nonlinear
Distortion
Limit

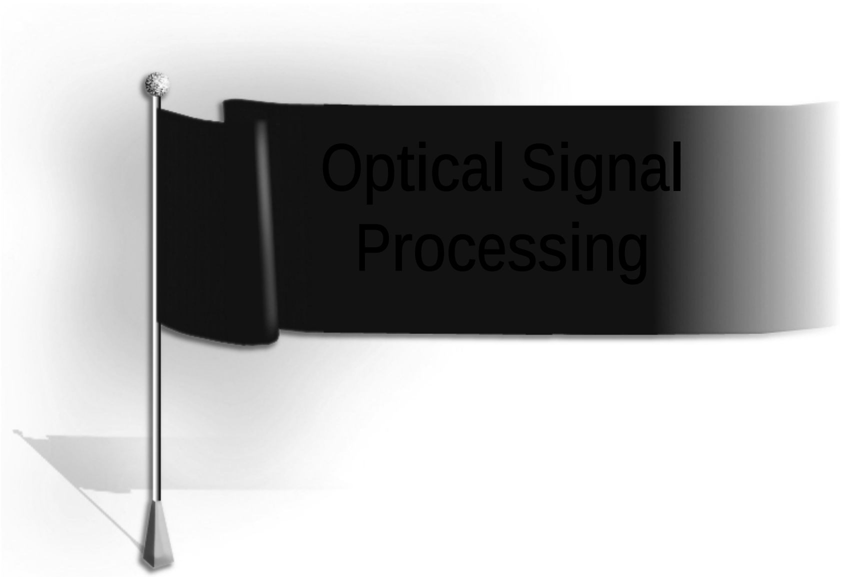
IEEE



Depends on *T*

$$T = \frac{m_{wlan}}{m_{wcdma,i}}$$

Nonlinear Distortion Limit



Optical Signal Processing

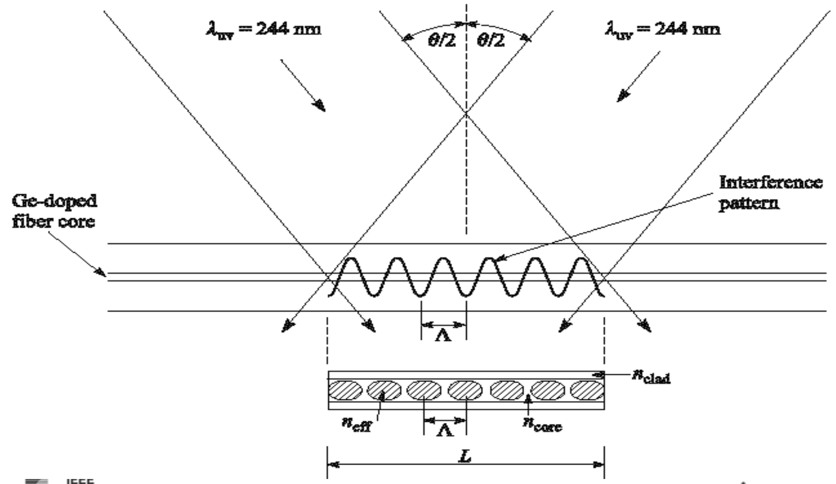
Microwave Photonics for ROF Systems

- Photonic generation of microwave signals
- All-Optical up/down conversion of RF signals
- All-Optical microwave filtering and signal processing
- Optical single sideband (OSSB) modulation
- Carrier power reduction

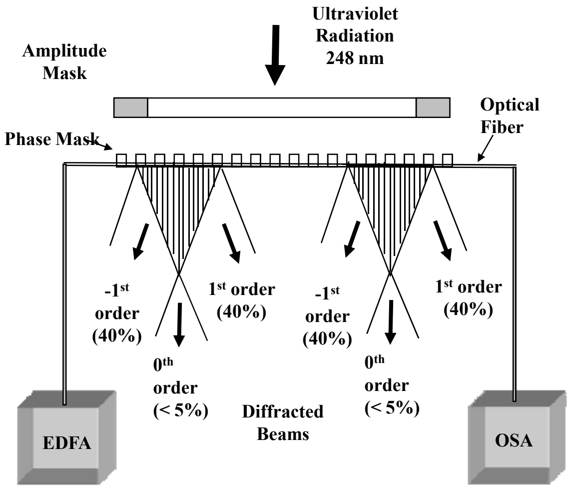
All Optical Microwave Signal Processing

- Bandpass, low pass and high pass, tuneable microwave photonic filters can be realized by
  - Optical delay lines (similar to tap delay line electrical filter)
  - Wavelength selective elements such fiber Bragg grating, waveguide arrays

Fiber Bragg Gratings



FP-FBG Fabrication



Phase mask technique

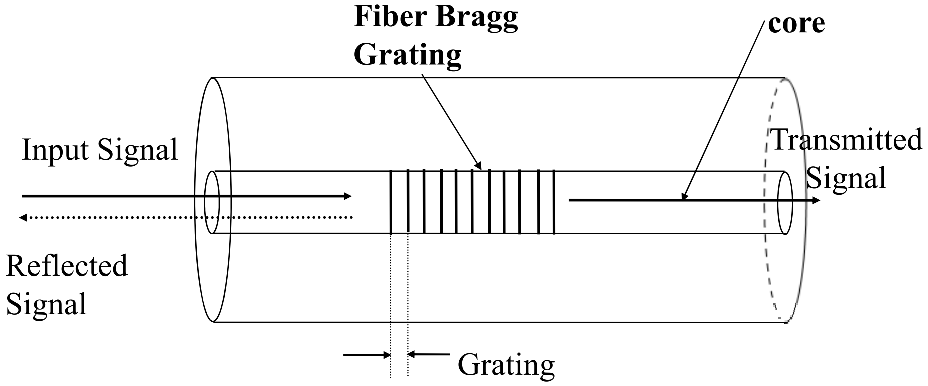
Amplitude mask is a double Sinc mask

Phase mask is a diffractive optical element

Fiber is a hydrogen loaded single mode fiber

$\Lambda_{Bragg} = \Lambda_{mask}/2$

Grating Structure in the Fiber Core

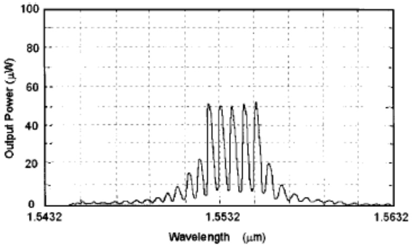


$\lambda_{Bragg} = 2\Lambda n_{eff}$

Microwave Generation

- Beating two light waves Δλ apart will generate an RF signal of frequency,

$$|\Delta\nu| = \left(\frac{c}{\lambda^2}\right)|\Delta\lambda|$$



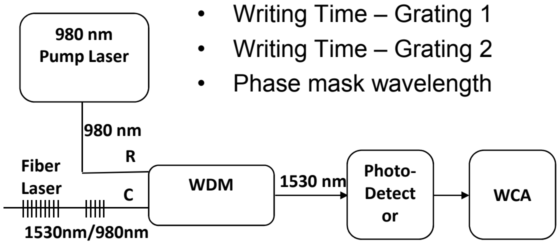
- Multiple wavelengths

→ multiple RF signals

- Light waves shall be
  - very stable, clean and narrow
  - Has low phase noise

Microwave Generation with single DBR Laser

- Reflectivity wavelength = 1533.773 nm
- 3 dB Bandwidth = 0.637 nm
- Laser Energy = 195 mJ
- Grating 1 Length 1 = 5 mm
- Grating 2 Length = 2.5 mm
- Writing Time – Grating 1 = 5 min 44 s
- Writing Time – Grating 2 = 2 min 10 s
- Phase mask wavelength = 1530.6 nm



980 nm Pump Laser

980 nm

R

Fiber Laser

C

1530nm/980nm

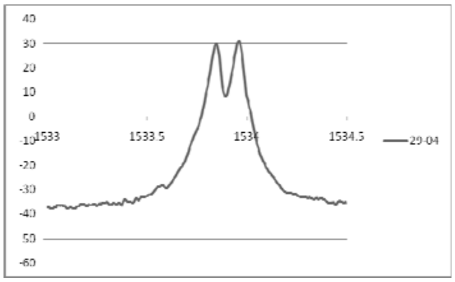
WDM

1530 nm

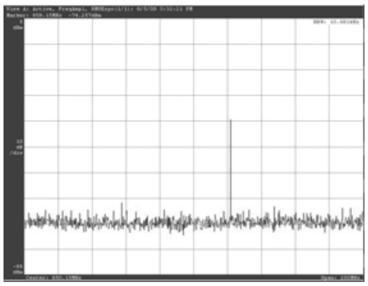
Photo-Detector

WCA

Microwave Generation with single DBR Laser



Laser spectra with two Longitudinal modes



Generated Microwave 858.8 MHz, Bandwidth 10.681 kHz

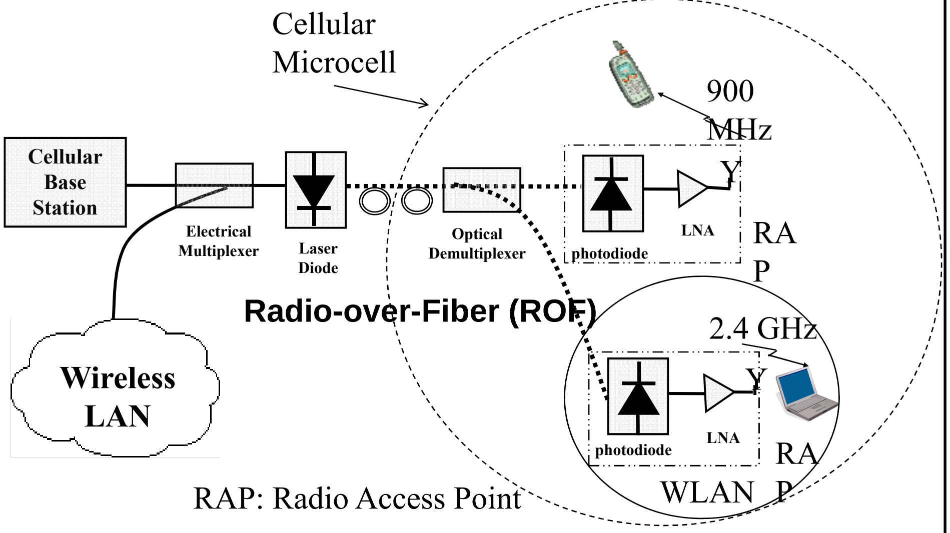
Up/Down Conversion

- Can be achieved using combinations of various nonlinear elements like:
  - Optical phase modulators
  - Intensity modulators
  - Dispersive fiber
  - Optical amplifiers (fiber/Semiconductor)
- Power loss during conversion is a concern

IEEE COMMUNICATIONS SOCIETY

IEEE

All-Optical Demultiplexing



RAP: Radio Access Point

IEEE COMMUNICATIONS SOCIETY

IEEE

All-Optical Demultiplexing

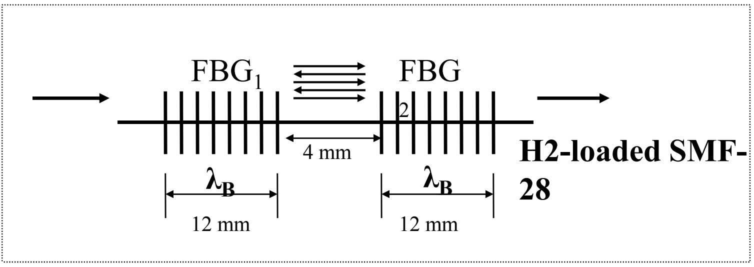
- Any RF subcarrier can be accessed at any point in the ROF network (suits PON)
- Unnecessary loss, noise and distortion due to O/E and E/O conversion are avoided.
- The photo detector can have low bandwidth (matched to only one subcarrier)
- Significant cost reduction

Narrowband FBG

- FBG-based narrow bandpass filters can be designed using two methods if the FBG length is limited between 15 mm and 30 mm.
  1. Induce a pi-phase in the middle of the FBG, which will create a narrow pass band in the middle of the FBG stop band.
     - -3 dB bandwidth as low as 0.5 pm
     - But high insertion loss
  2. Induce two FBGs with identical wavelength. This method results in multiple resonant peaks in the stop band.
     - Low insertion loss

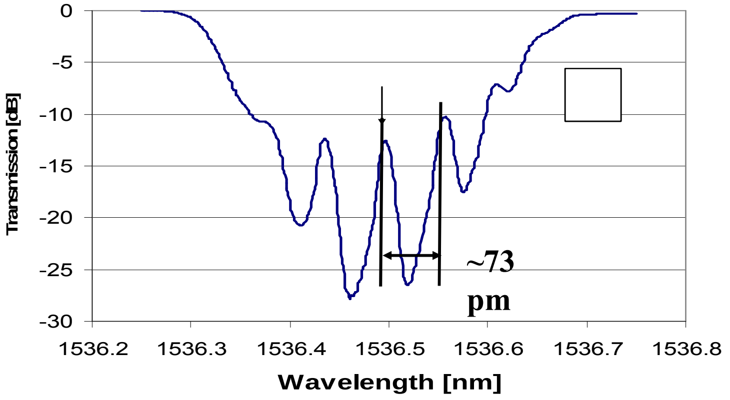
FBG-Based Resonance Filter

- A highly reflective filter with a bandwidth in the sub-Pico meter range was imprinted using two highly reflective FBGs, which formed a resonator
- The overall length of the filter is 28mm



Resonance Filter

- The stop bandwidth of the FBG was ~ 0.3 nm at -3 dB and five resonant peaks were created.
- The bandwidth of the resonant peak is determined by the length of the resonator and the reflectivity of the FBG.

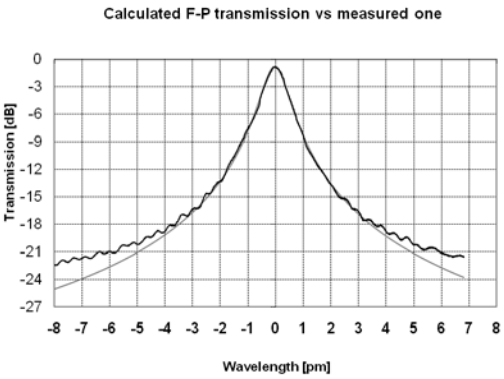


Filter Transfer Function

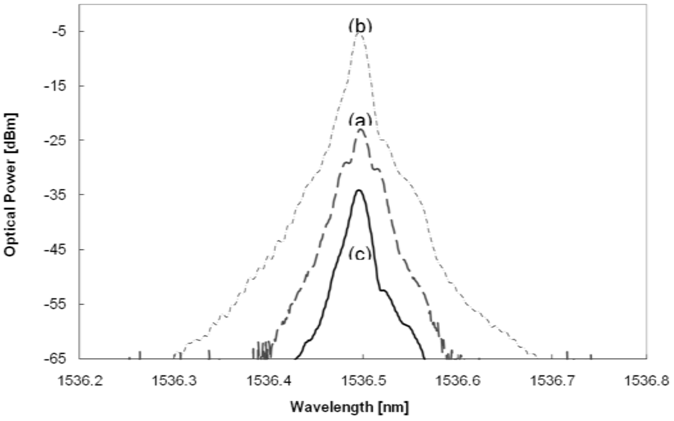
The spectrum of resonant peak (black trace) was obtained by scanning the sideband over a 2 GHz range at 4 MHz per step. The red trace was the calculate

planer Fabry-Perot resonator.

- The filter has a bandwidth of
  120 MHz at -3 dB
  360 MHz at -10 dB
  1.5GHz at -20 dB
- The insertion loss is 0.8 dB at the resonant peak.
- Filter is polarization sensitive

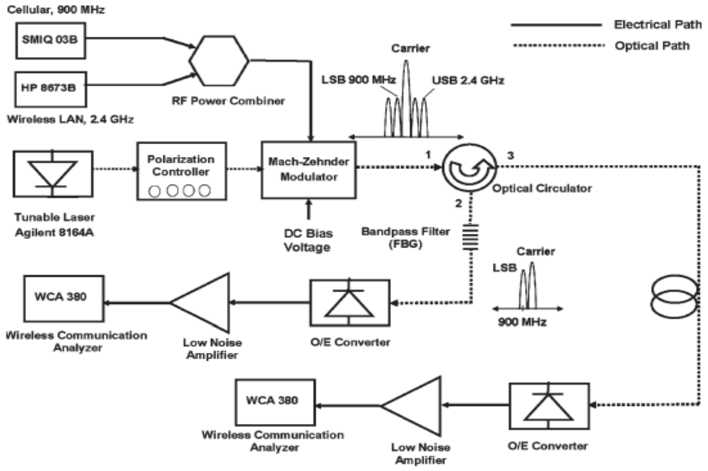


Optical Spectra at MZM Output

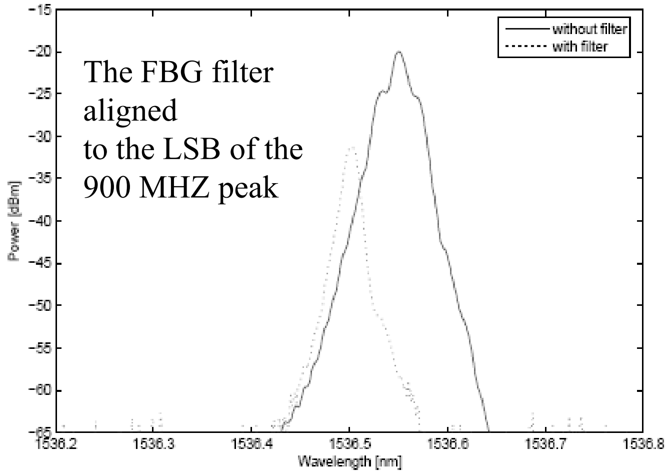


(a) Output of the MZM when the DC bias is tuned to non-linear region
(b) When DC bias is tuned to linear region
(b) Sideband are not visible at this bias condition

Demux Experiment

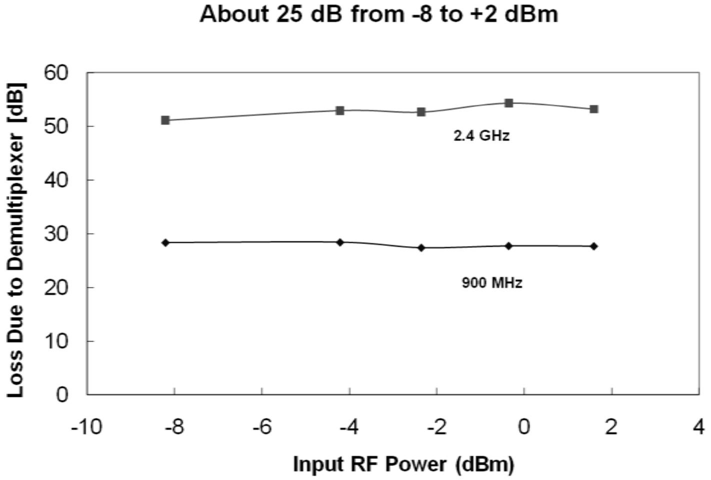


Filtered Spectrum



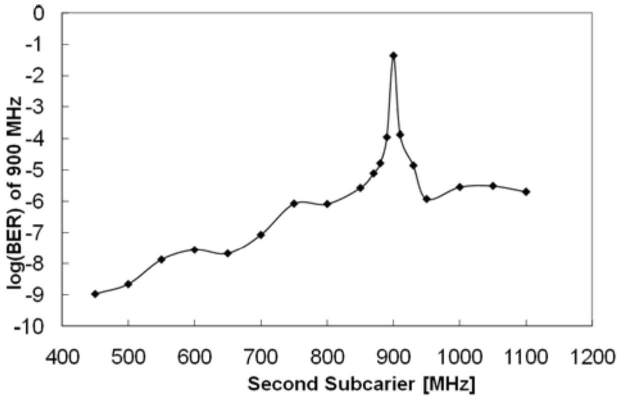
The FBG filter aligned
to the LSB of the
900 MHZ peak

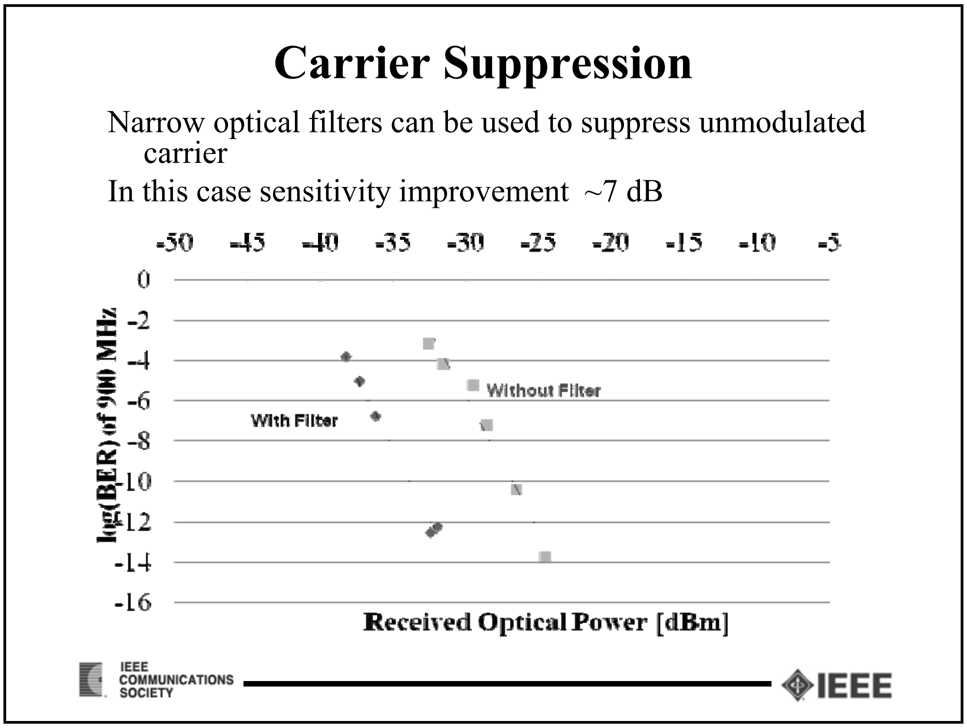
Selectivity of the Demultiplexer


About 25 dB from -8 to +2 dBm

Frequency Separation of the Filter

- The BER performance of 900 MHz signal at the filter output as the 2nd subcarrier was swept from 450 MHz to 1.1 GHz
- The BER level at 50 MHz separation is 2.72×10^{-6}

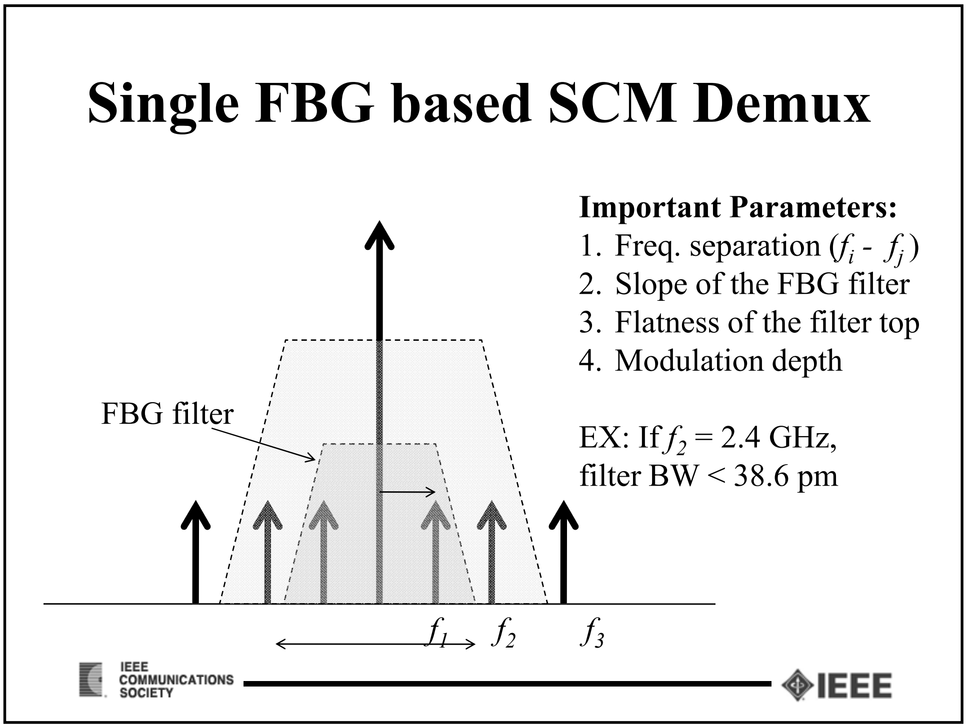




Carrier Suppression

Narrow optical filters can be used to suppress unmodulated carrier

In this case sensitivity improvement ~7 dB

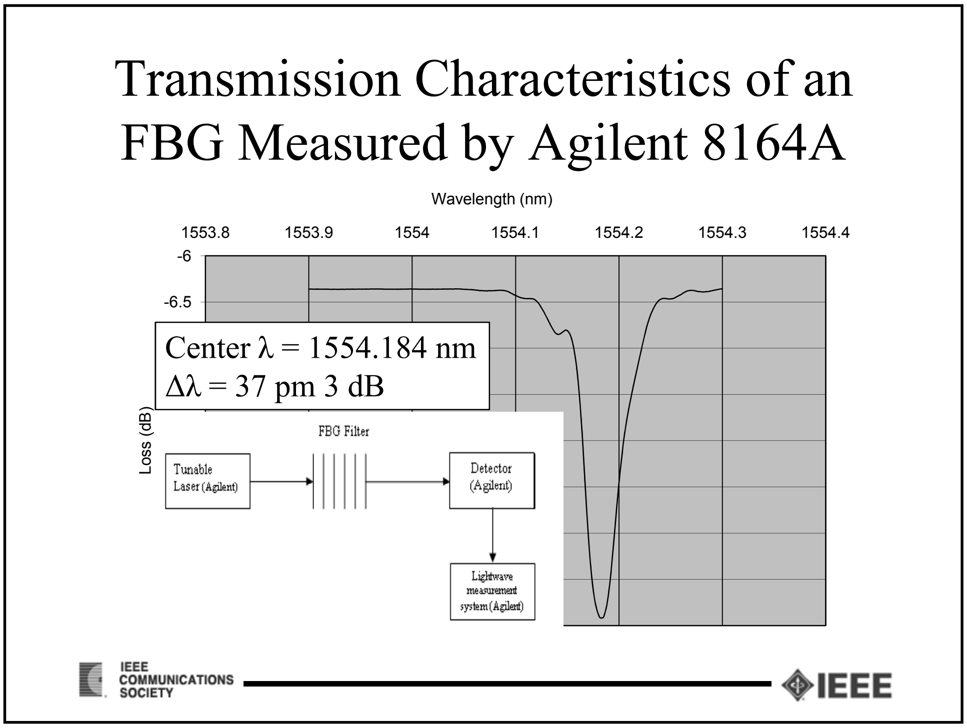


Single FBG based SCM Demux

Important Parameters:

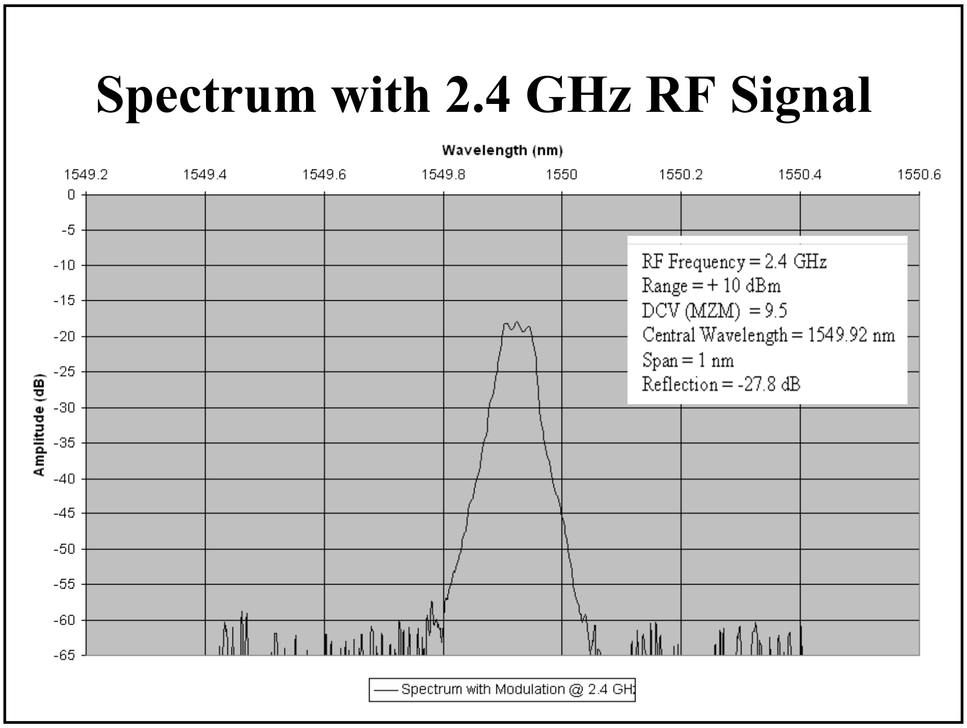
1. Freq. separation (f_i - f_j)
2. Slope of the FBG filter
3. Flatness of the filter top
4. Modulation depth

EX: If f_2 = 2.4 GHz, filter BW < 38.6 pm



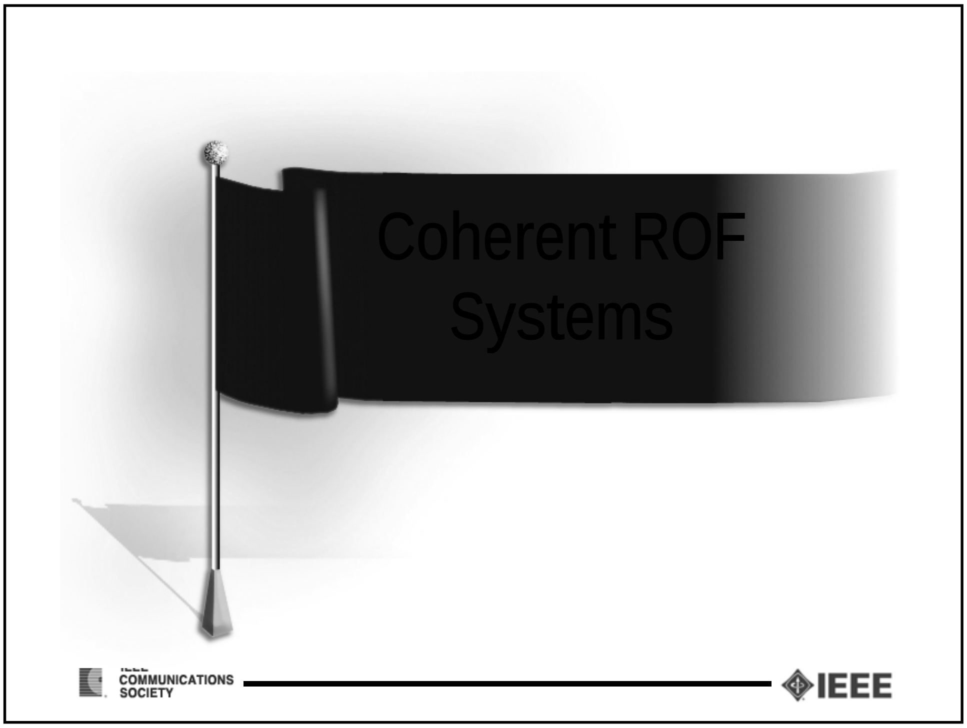
Transmission Characteristics of an FBG Measured by Agilent 8164A

Center λ = 1554.184 nm
Δλ = 37 pm 3 dB



Spectrum with 2.4 GHz RF Signal

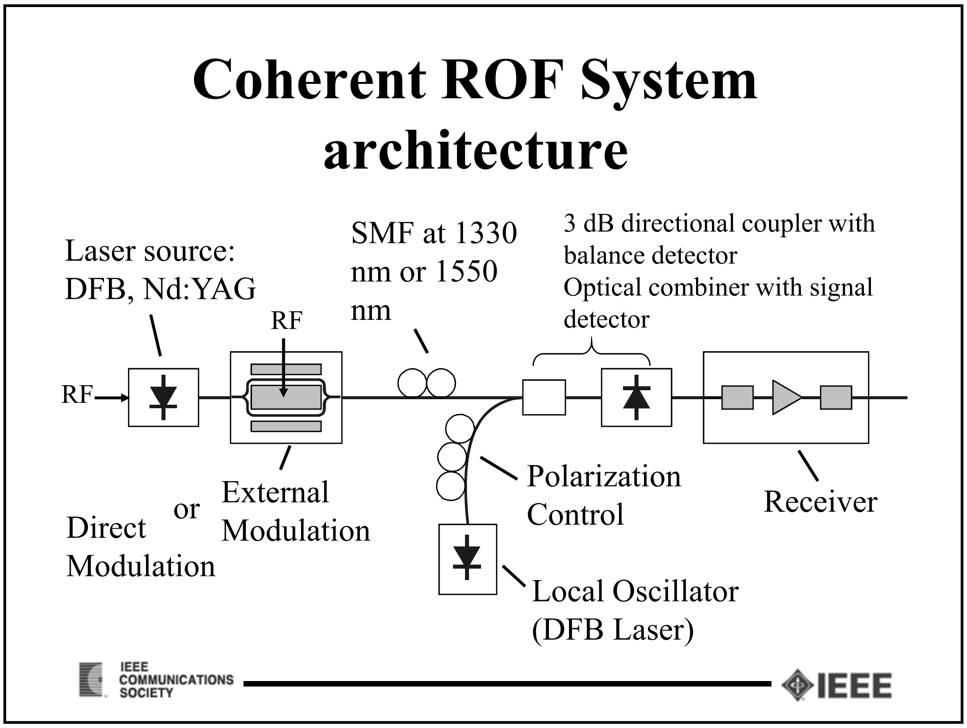
RF Frequency = 2.4 GHz
Range = + 10 dBm
DCV (MZM) = 9.5
Central Wavelength = 1549.92 nm
Span = 1 nm
Reflection = -27.8 dB



Coherent ROF Systems

IEEE COMMUNICATIONS SOCIETY

IEEE



Coherent ROF System architecture

IEEE COMMUNICATIONS SOCIETY

IEEE

Coherent Systems…

- Amplitude or Angle Modulation (PM, FM) is possible with coherent systems
- Angle modulation has higher Spurious Free Dynamic Range (SFDR) to handle large dynamic range requirement of the air
- External coherent modulation gives power gain while direct coherent modulation gives power loss

Coherent Systems…

- Relative intensity noise (RIN) is proportional to the square of the mean optical power.
- A balance coherent receiver (with closely matched photodiodes) can cancel majority of the RIN
- Optical signal sideband (OSSB) can be easily done with coherent systems [6]
- External modulation give 70 GHz and direct modulation gives 20 GHz electrical bandwidths respectively [2]

Coherent Systems…

- Angle modulation systems have phase noise
- Phase noise cancellation schemes could further increase SFDR in angle modulation
- Potential system to employ angle modulation with external phase modulator
- However, coherent systems:
  - Are more expensive
  - Need phase locked receivers
  - Need very stable and narrow line width lasers

RF over MMF

- Multimode Fiber (MMF)
  - Predominant in-building backbones
  - High coupling efficiency – 90%
  - Simple coupling technique – butt coupling
  - But low bandwidth (typically 500 MHz.km at 1300 nm) due to modal dispersion
  - Hence IF over MMF is dominant
- RF over MMF
  - low installation cost combined with low complexity

WDM ROF

- ✓Will be the future
- ✓Existing dim fibers can be effectively used
- ✓Emerging FTTx networks can carry additional SCM RF wavelengths
- Very high linearity requirements
- High isolation requirements for WDM de-multiplexers
- Cost considerations

Conclusions

- Radio over Fiber is an attractive approach for wideband wireless access
- Fiber has ample bandwidth
- Lots of existing dim/dark fiber
- Supporting multiple standards is possible
- Major concerns are
  - High loss and noise due to concatenated channels
  - Nonlinear distortion and limited dynamic range
- Some emerging areas like coherent modulation will improve the situation

References

[1] An analytic and experimental comparison of direct and external modulation in analog fiber-optic links
Cox, C.H., III; Betts, G.E.; Johnson, L.M.;
Microwave Theory and Techniques, IEEE Transactions on , Volume: 38 Issue: 5 , May 1990
Page(s): 501 –509

[2] Direct-detection analog optical links
Cox, C., III.; Ackerman, E.; Helkey, R.; Betts, G.E.;
Microwave Theory and Techniques, IEEE Transactions on , Volume: 45 Issue: 8 , Aug. 1997
Page(s): 1375 –1383

[3] Dynamic range of coherent analog fiber-optic links
Kalman, R.F.; Fan, J.C.; Kazovsky, L.G.;
Lightwave Technology, Journal of , Volume: 12 Issue: 7 , July 1994
Page(s): 1263 –1277

[4] On the design of optical fiber based wireless access systems..
Fernando X. N.; Anpalagan A.;
WINCORE laboratory, Ryerson University, Toronto

[5] Optically coherent direct modulated FM analog link with phase noise canceling circuit
Taylor, R.; Forrest, S.;
Lightwave Technology, Journal of , Volume: 17 Issue: 4 , April 1999
Page(s): 556 –563

[6] Technique for optical SSB generation to overcome dispersion penalties in fiber-radio systems
Smith, G. H.; Novak D.; Ahmed Z;

[7] Phase noise in coherent analog AM-WIRNA optical link
Tayor R.; Poor H. V.; Forrest Stephen;